Photons and Dileptons as Probes in the ~~pre~~-RHIC Era

non

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direct photons and dileptons (e+e-, μ+μ-):

- probe dynamics of nucleus-nucleus collisions
- evidence for thermal radiation from an equilibrated source

direct photons: TAPS, WA98

dileptons (e^+e^-, $\mu+\mu^-$): $\Rightarrow$ continuum and resonances:
in-medium properties of hadrons:
(mass, width), partonic contributions?

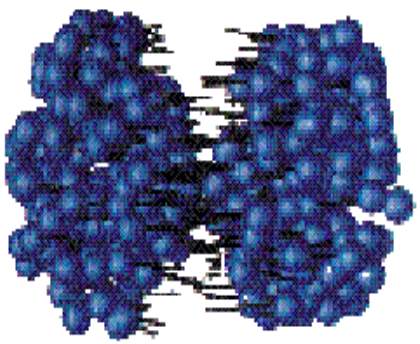
a.) nucleus-nucleus-collisions: HELIOS, CERES, NA50, NA60
DLS, HADES,

b.) elementary reactions: KEK E235, CLAS (Jlab),
HADES, (CBELSA/TAPS)

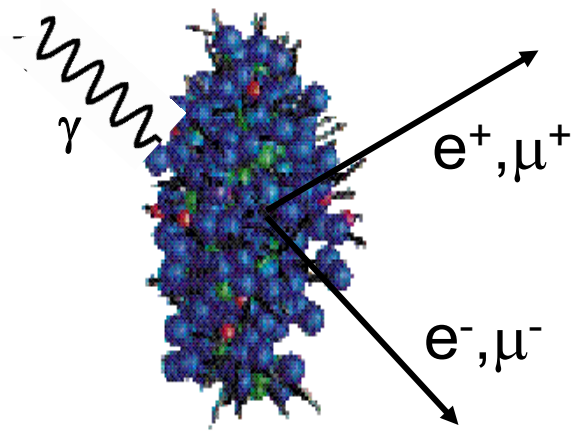
RHIC-AGS-users meeting, BNL, 27.5.2008

Photons and dileptons as probes in heavy-ion reactions

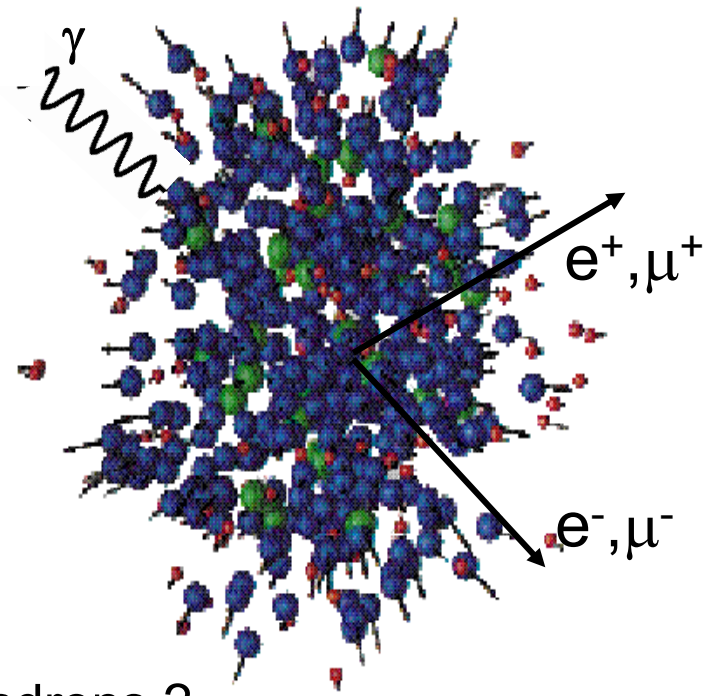
two colliding nuclei
A+A @ 2 AGeV



formation of highly compressed and heated collision zone



explosion of collision zone

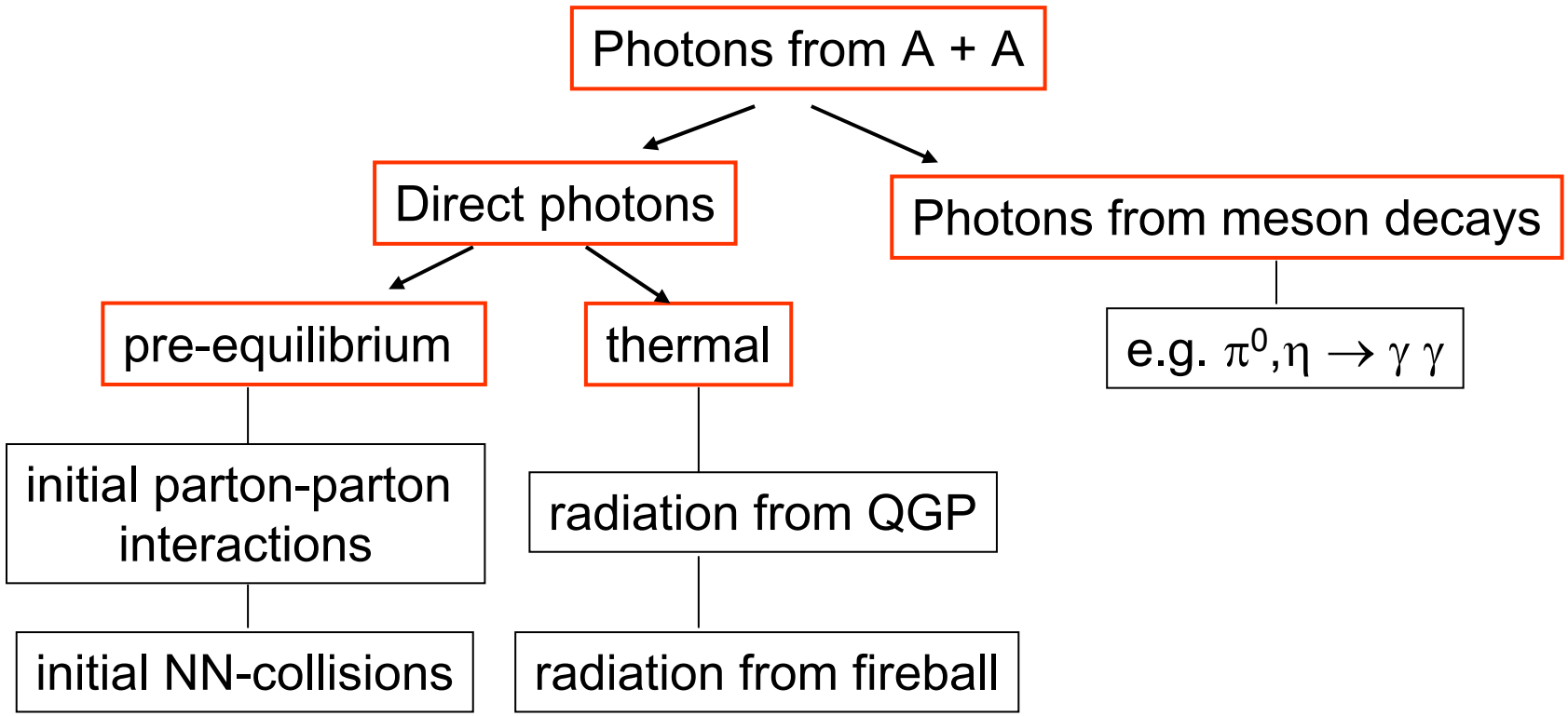


- collision zone: new forms of matter? / medium modifications of hadrons ?
- photons:
- dileptons:

probe the full space-time evolution of the collision, being emitted through all stages of the reaction

- photons and dileptons: undistorted probes of strongly interacting matter

Photons from nucleus-nucleus collisions

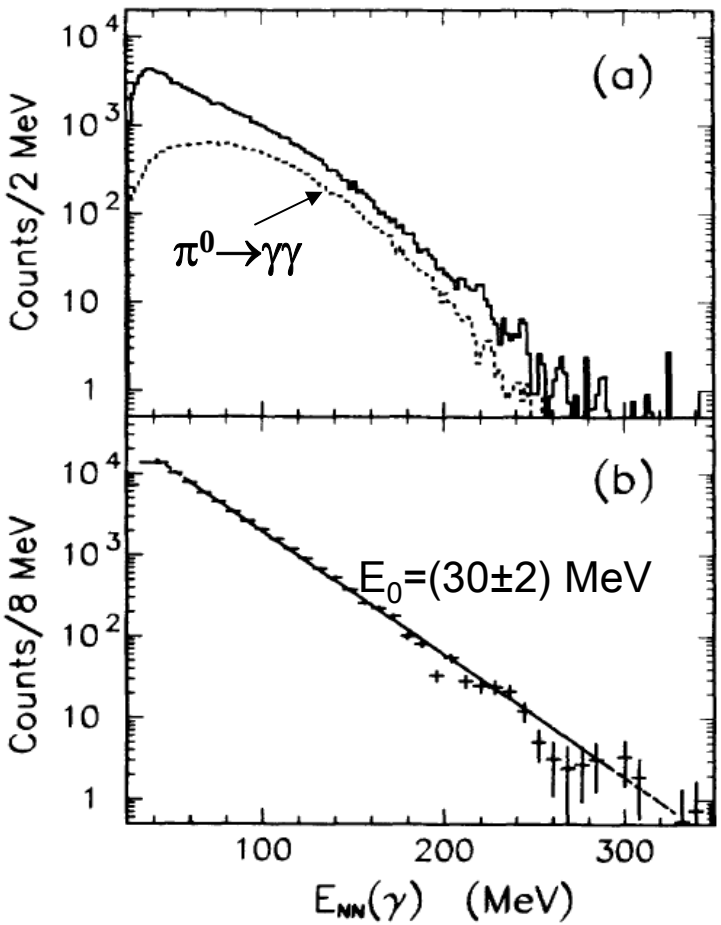


Photons from heavy-ion collisions near the π - threshold

A. Schubert et al. PRL 72 (1994) 1608

^{36}Ar + Au @ 95 MeV/u

TAPS@GANIL



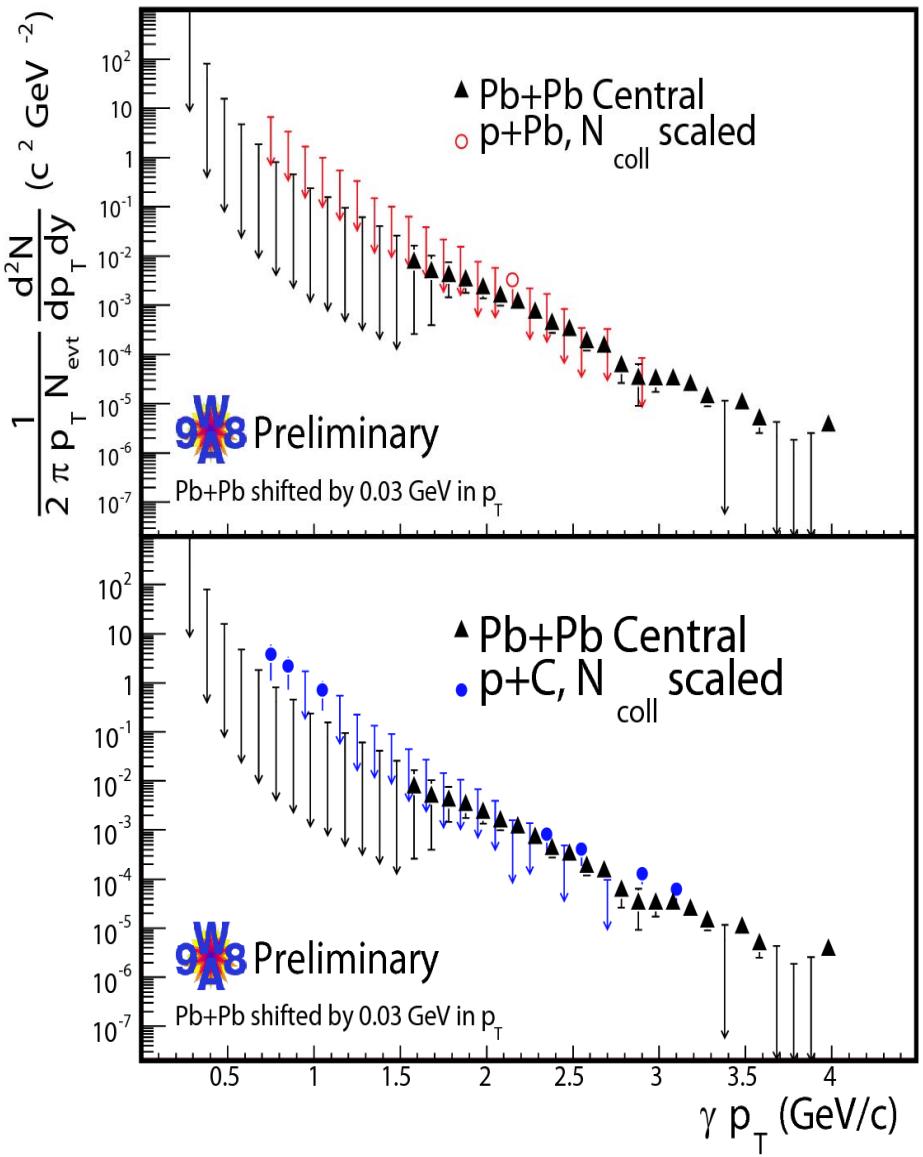
- direct photons contaminated by photons from meson decays, here: $\pi^0 \rightarrow \gamma\,\gamma$.
  contribution subtracted via simulations based on measured π^0 spectra
- almost purely exponential spectrum in nucleon-nucleon system: $N_\gamma \sim e^{-\frac{E_\gamma}{E_0}}$
- origin: initial p – n collisions;
  slowing down due to the strong interaction
  bremsstrahlung due to e.m.-interaction
- information on reaction dynamics:
  time scales: $\Delta t = \frac{\hbar}{E_0} \approx 7\,\frac{\text{fm}}{\text{c}}$
- analysis of photon angular distribution shows for Ar+C: $\beta_{source} \approx \beta_{NN}$
  for Ar+Au: $\beta_{AA} < \beta_{source} < \beta_{NN}$

$\Rightarrow$ hard photons do not only probe the very first phase of heavy-ion collisions but carry information on the later stopping phase of the collision

hard photons from ultra-relativistic nucleus-nucleus collisions

WA98@CERN/SPS

C. Baumann et al., QM_08

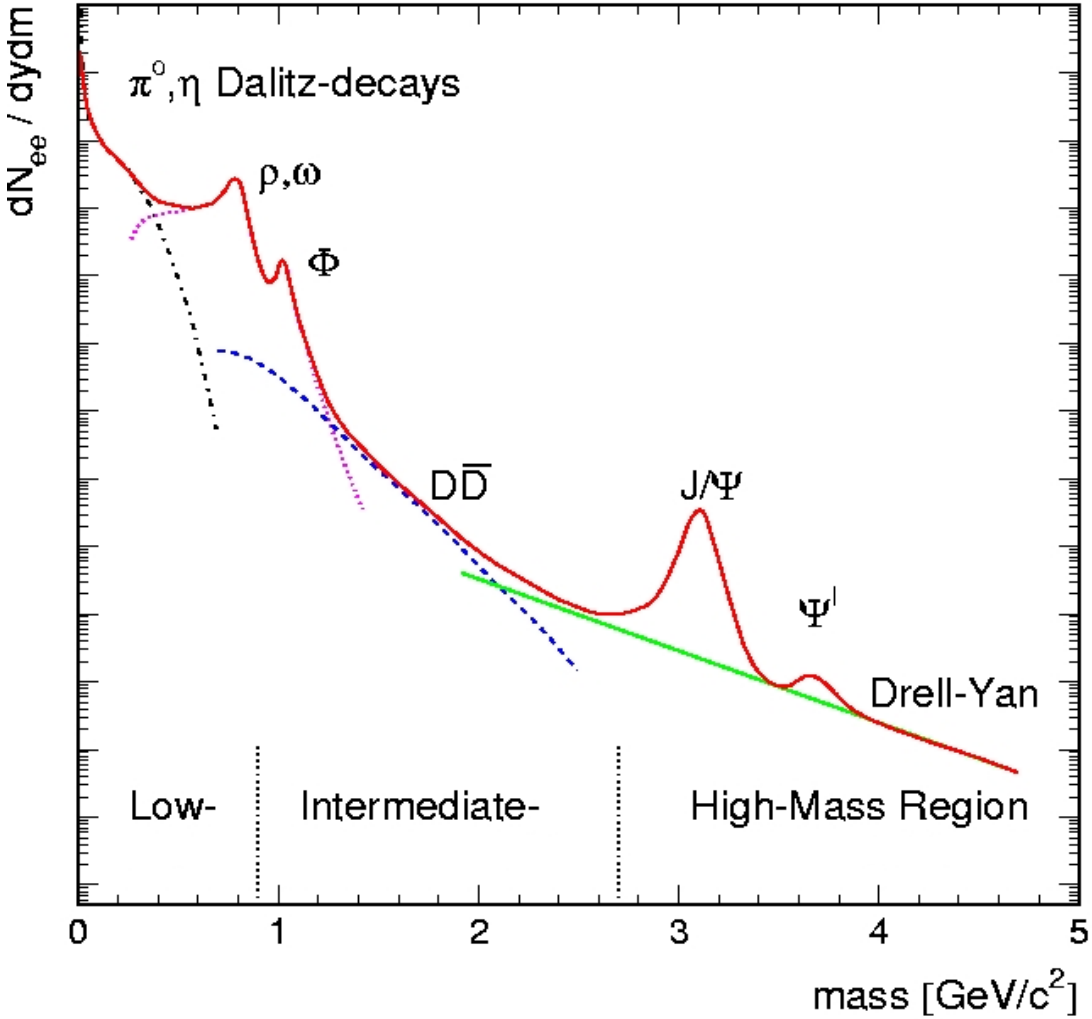


- comparison of direct photons from Pb+Pb with p+C and p+Pb (after statistical subtraction of photons from hadron decays; scaled by number of N-N collisions)
- for p_t > 2.5 GeV/c direct photon yield in Pb+Pb consistent with observed yield in hard N-N scattering
  and
  consistent with pQCD predictions (difficult to obtain at SPS energies
- for p_t < 2.5 GeV/c room for thermal photon signal (Reygers, nucl-ex/0611004)
- initial temperatures for central Pb+Pb collisions: 200 < T_i < 370 MeV

evidence for thermal photons ⇒ RHIC

Dilepton invariant mass spectra

- characteristic features of dilepton invariant mass spectra



Physics issues

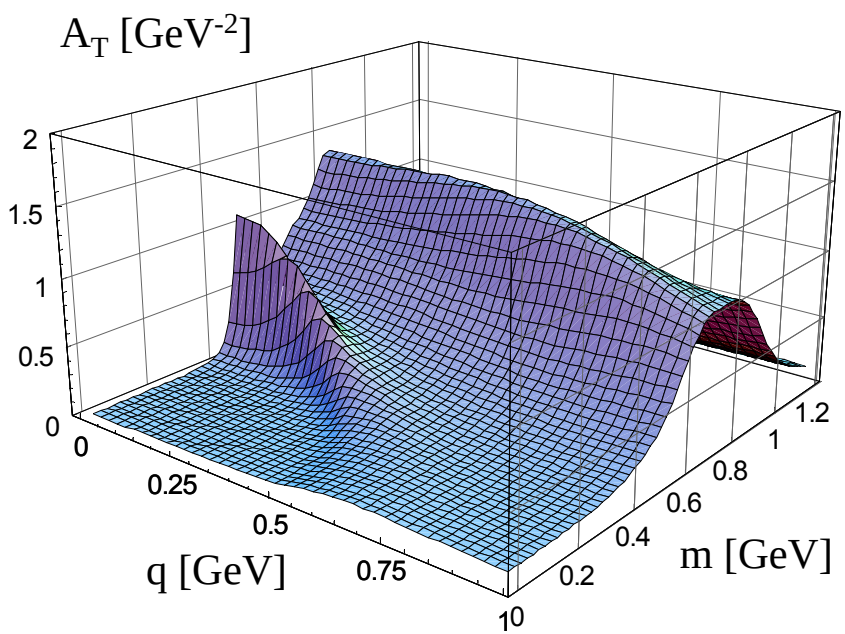
- Low mass:
  - continuum enhancement ?
  - modification of vector mesons ?
- intermediate mass:
  - thermal radiation ?
  - charm modification
- High mass:
  - J/ψ suppression ?
    enhancement ?
  - Drell-Yan

- in this talk focus on low mass and intermediate mass region

Predicted medium modifications of the ρ meson

- as a function of baryon density

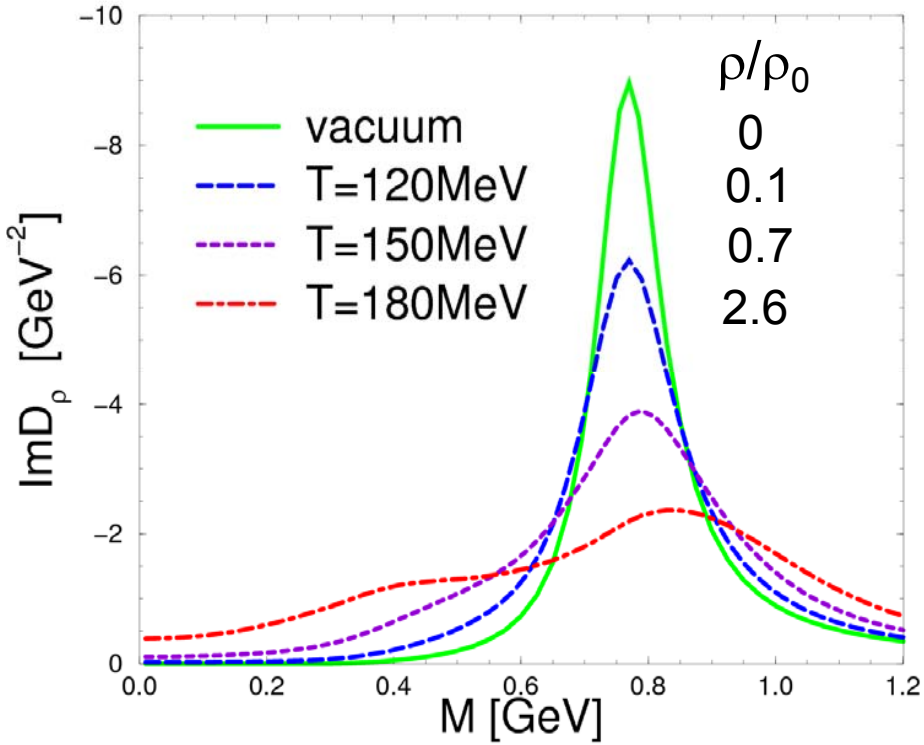
M. Post et al., NPA 741 (2004) 81



- structure in spectral function due to meson-N* coupling ⇒ strong momentum dependence; modifications limited to small momenta

- as a function of baryon density and temperature

R. Rapp and J. Wambach, EPJA 6 (1999) 415



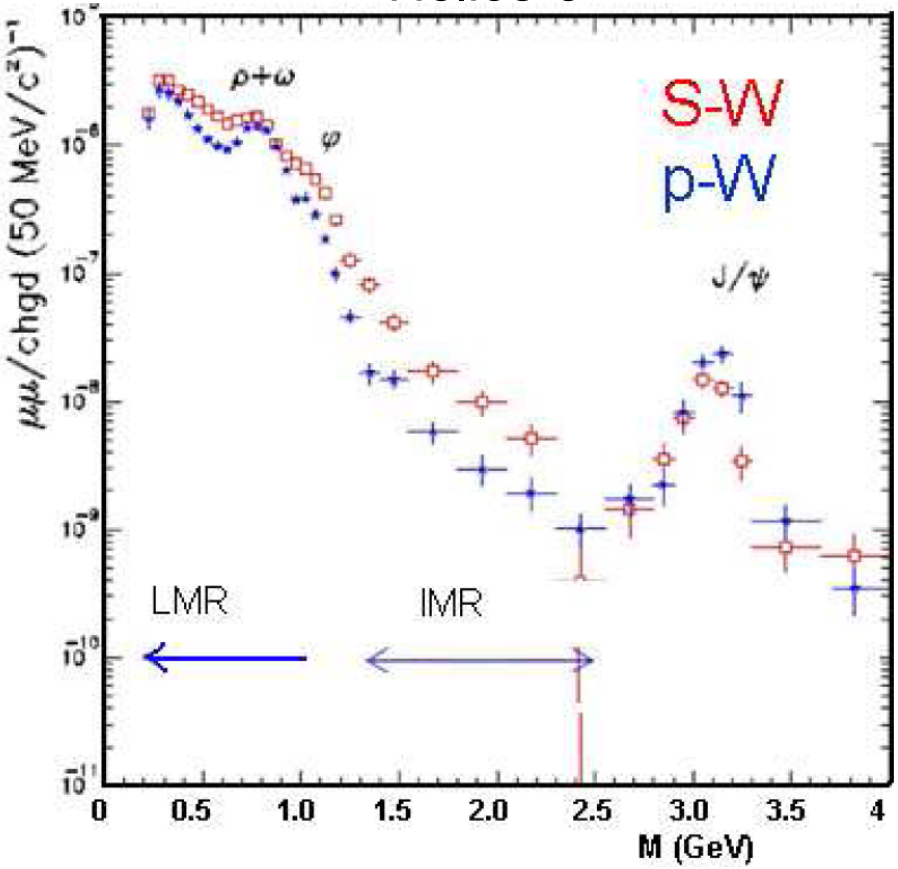
- distribution of ρ - strength over wide mass range: ⇒ broadening

Di-muon spectra from Helios-3 and NA50 @CERN/SPS

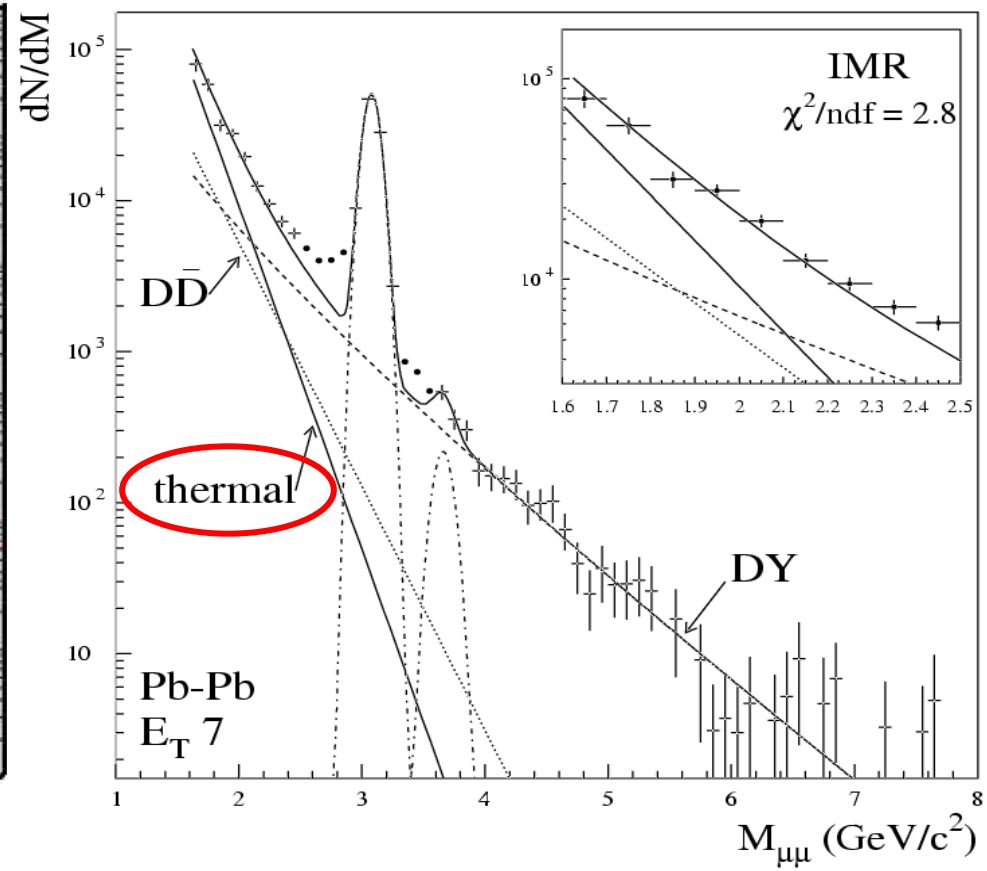
M. Masera et al., NPA590 (1995) 93c
A.L.S. Angelis et al., EPJC 13 (2000) 433

M.C. Abreu et al., NPA 698 (2002) 539

Helios-3



NA38/NA50



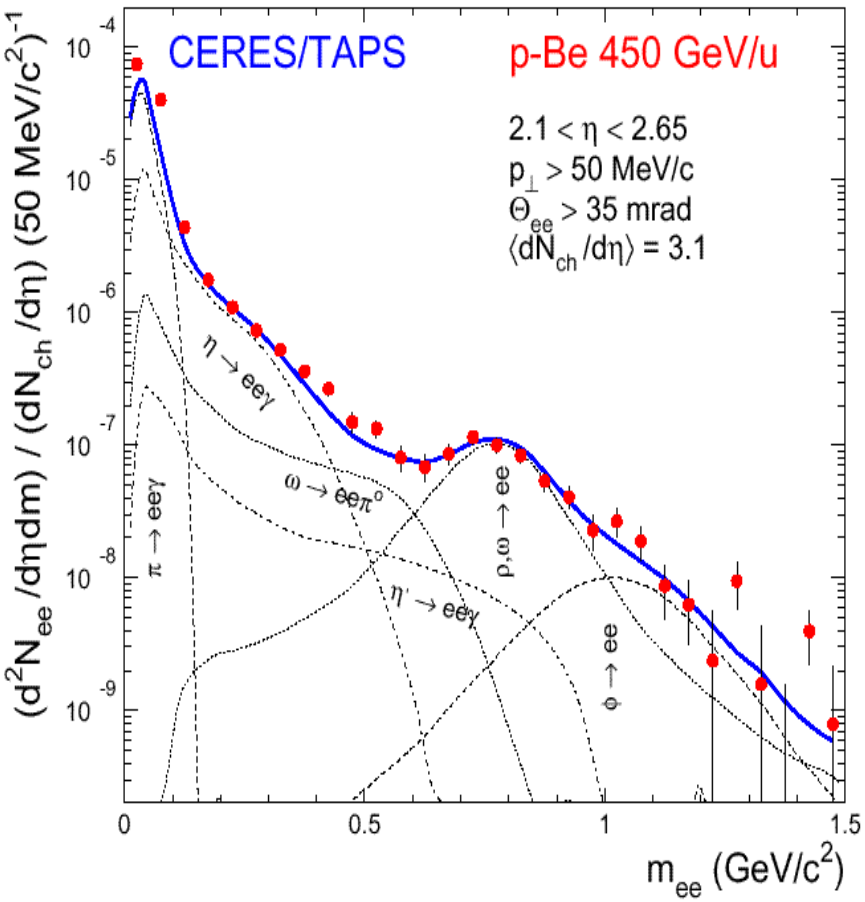
- enhancement of $\mu^+\mu^-$ pairs extends over full kinematic range in invariant mass $m_{\mu\mu}$

- open charm decays on top of Drell-Yan contributions; excess: thermal radiation or open charm?

CERES@CERN/SPS

G. Agakishiev et al. EPJ C4 (1998) 231

e^+e^- production in elementary NN reactions

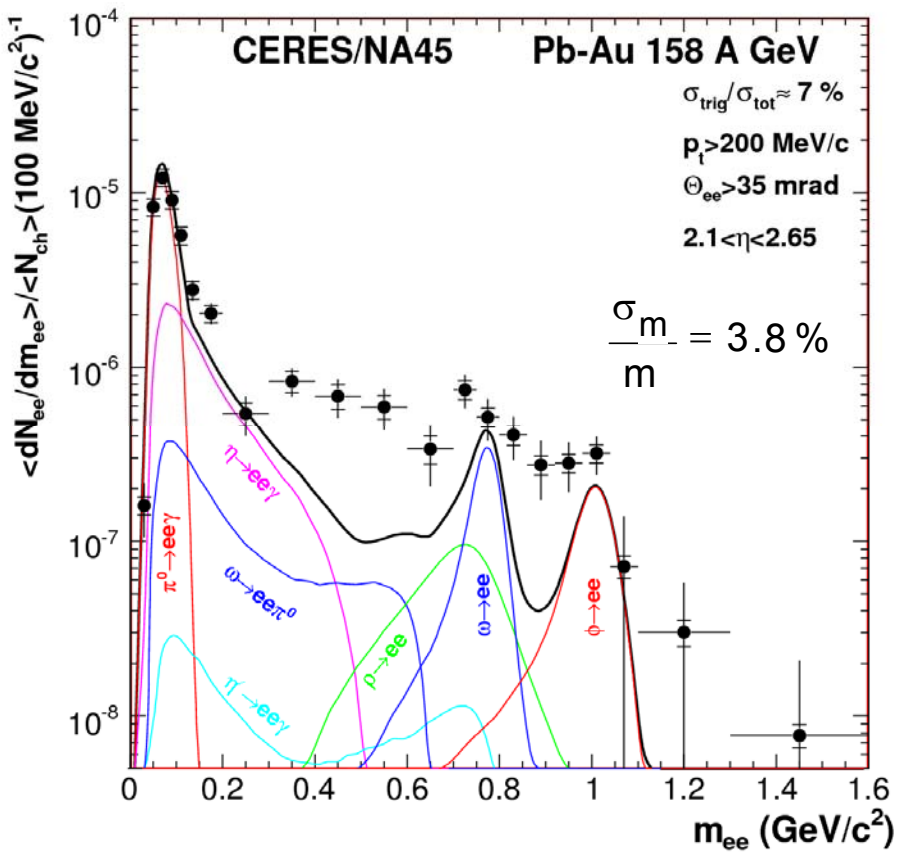


e^+e^- yield reproduced by cocktail of known hadronic sources

G. Agakishiev et al., PRL 75 (1995)1272

D. Adamova et al. nucl-ex/0611022

A+A data in comparison to post-freeze-out hadronic cocktail



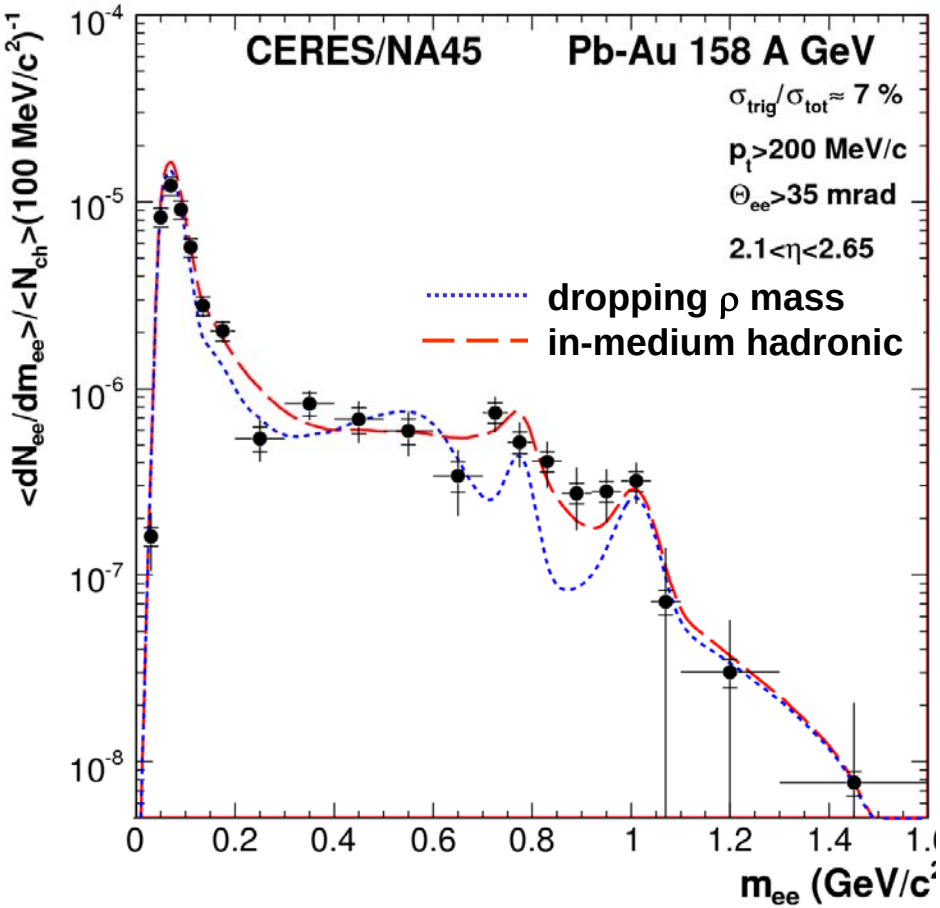
excess over hadronic decay cocktail attributed to annihilation of thermal pions

$\pi+\pi- \rightarrow \rho \rightarrow e+e-$

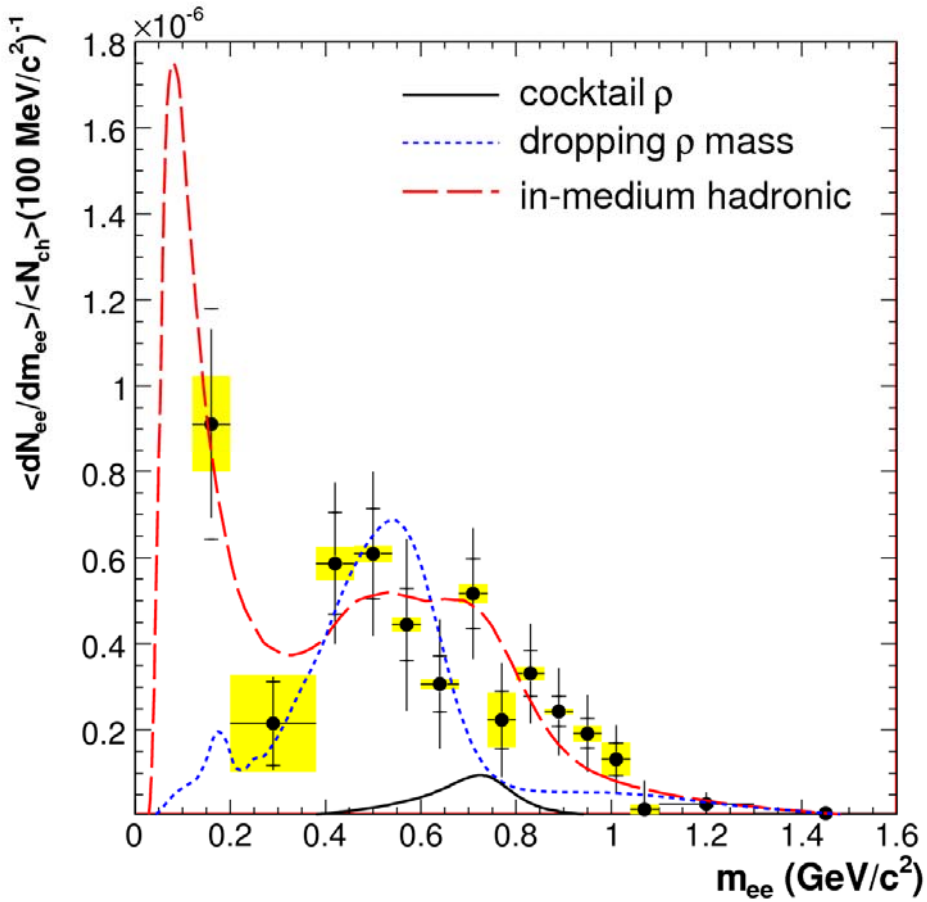
CERES@CERN/SPS

comparison to transport calculations

R. Rapp, J. Wambach EPJA 6 (1999) 415
H. Hees, R. Rapp PRL 97 (2006) 102301



e+e- pair yield after subtraction of hadronic cocktail excluding ρ:



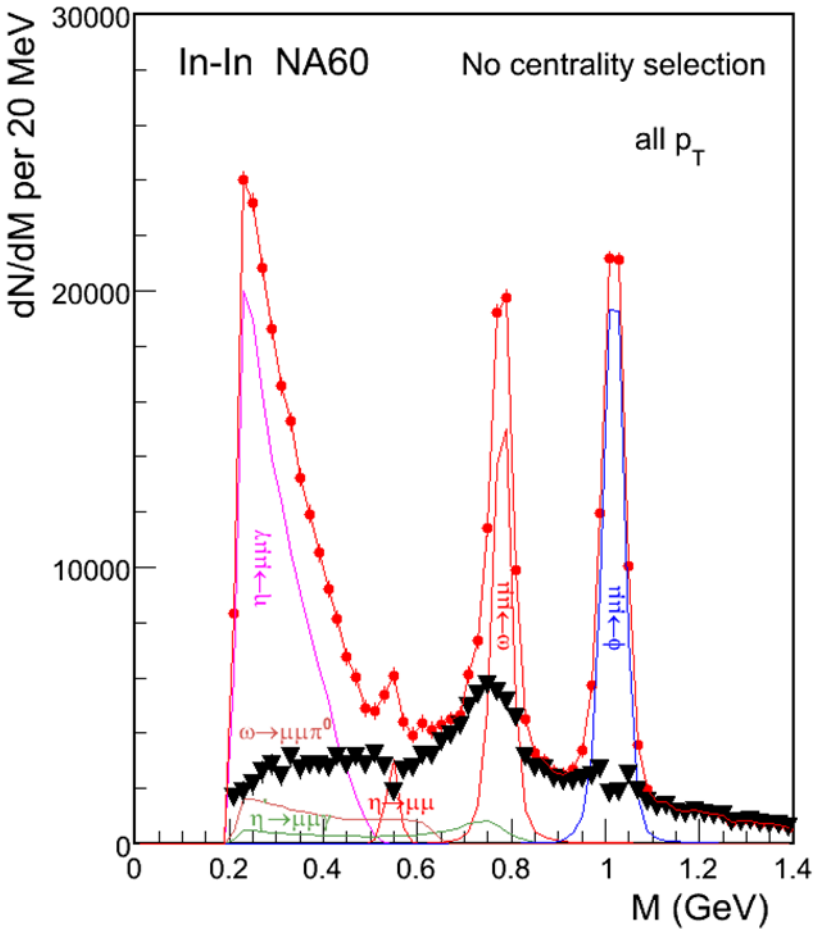
- in particular e^+e^- yield between ω and ϕ favours ρ broadening over dropping mass scenario

- excess smeared out over wider mass range than expected for dropping ρ mass scenario

NA60@CERN/SPS: invariant mass spectra

R. Arnaldi et al., PRL 96 (2006) 162302

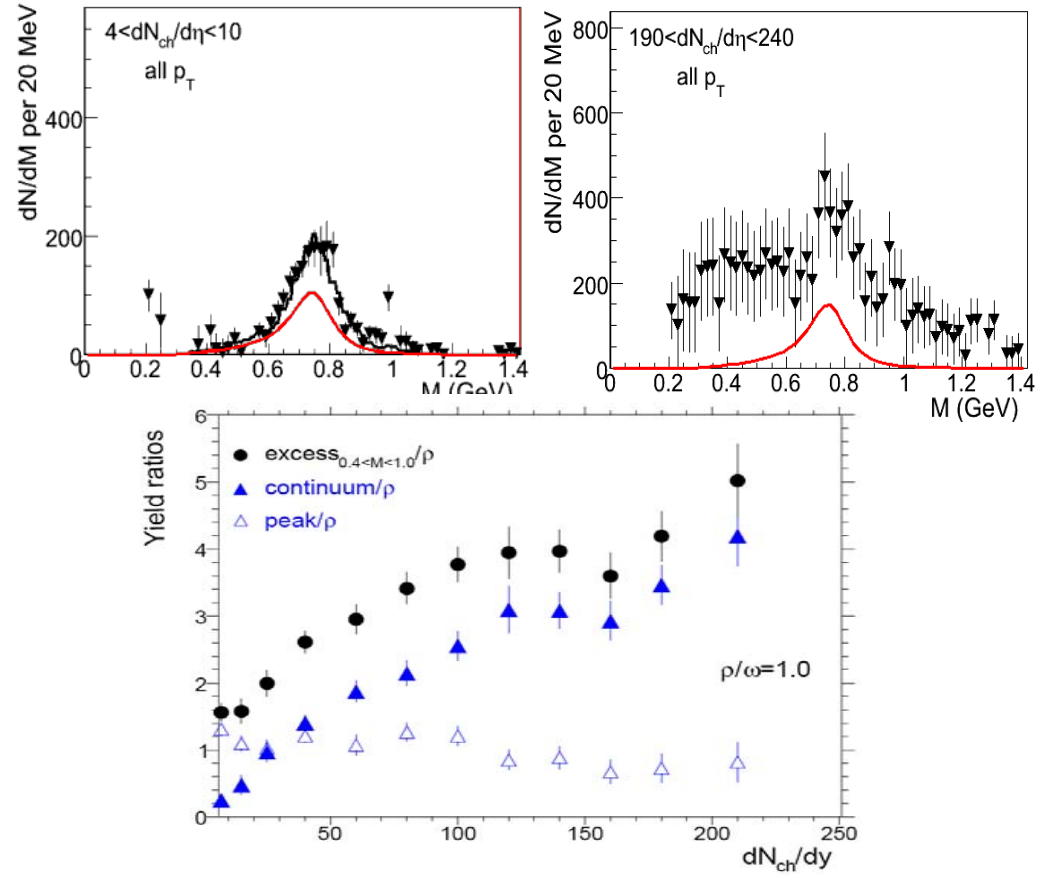
di-muon excess in 158 AGeV In+In



- isolation of excess by subtraction of the measured decay cocktail

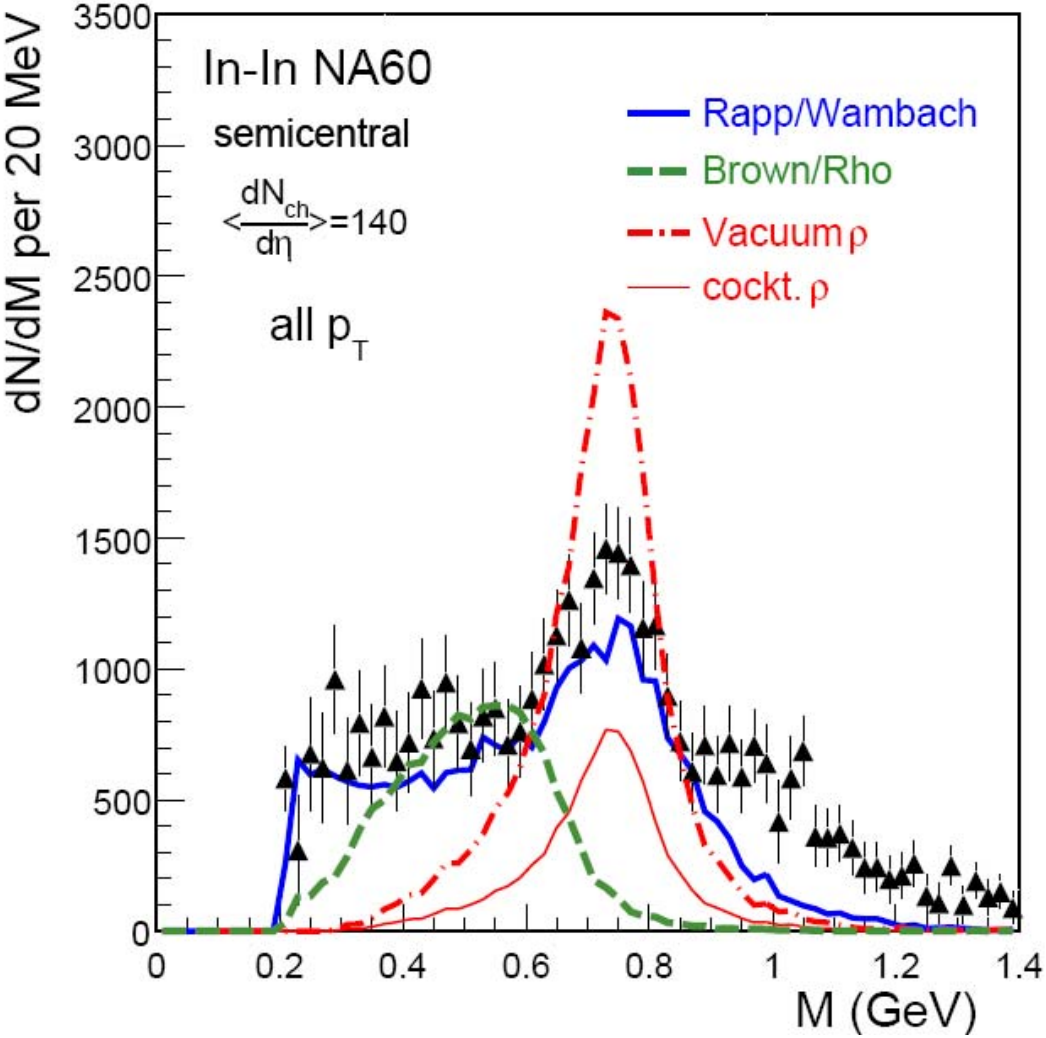
S. Damjanovic et al., EPJC 49 (2007) 235

centrality dependence of excess



- excess rising with centrality; centered at the nominal ρ-pole
- monotonic broadening of excess with centrality ⇒ „melting“ of the ρ

Comparison of NA60 data to transport calculations



Two theoretical scenarios for ρ in-medium spectral function

a.) broadening

Rapp/Wambach Ad.N.P. 25 (200) 1

b.) dropping mass

Brown/Rho Phys. Rep. 363 (2002) 85

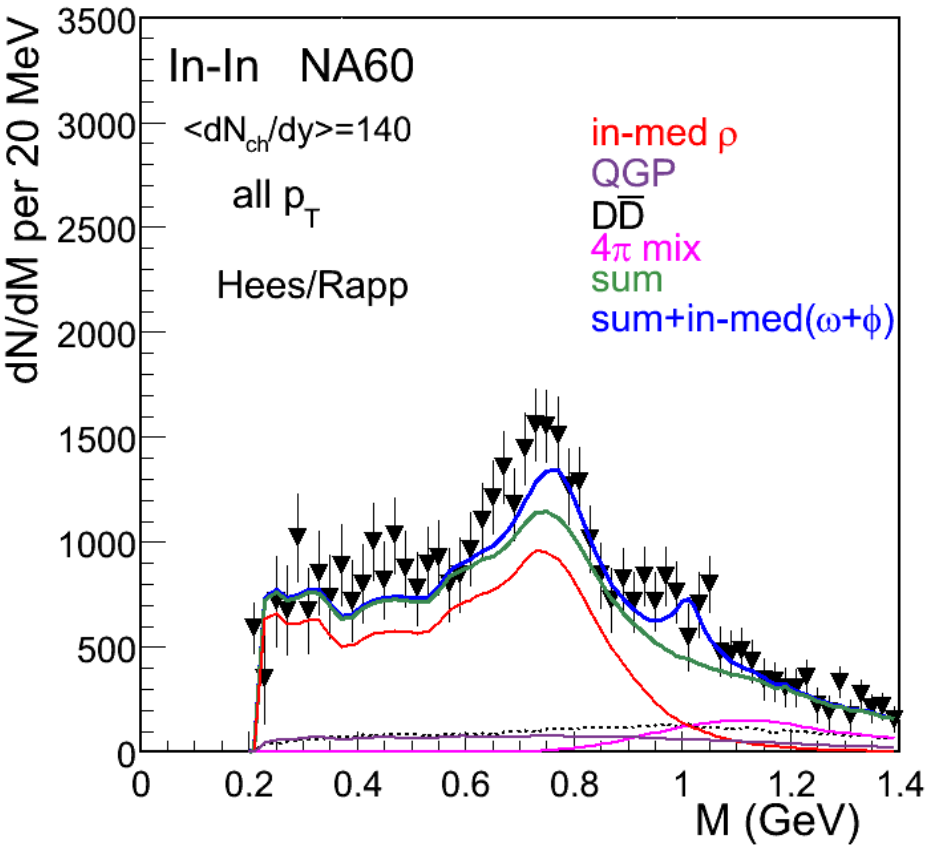
evaluated for the same fireball evolution (R. Rapp 2003) (keeping the original normalization)

⇒ dropping mass scenario fails to reproduce precise NA60 data

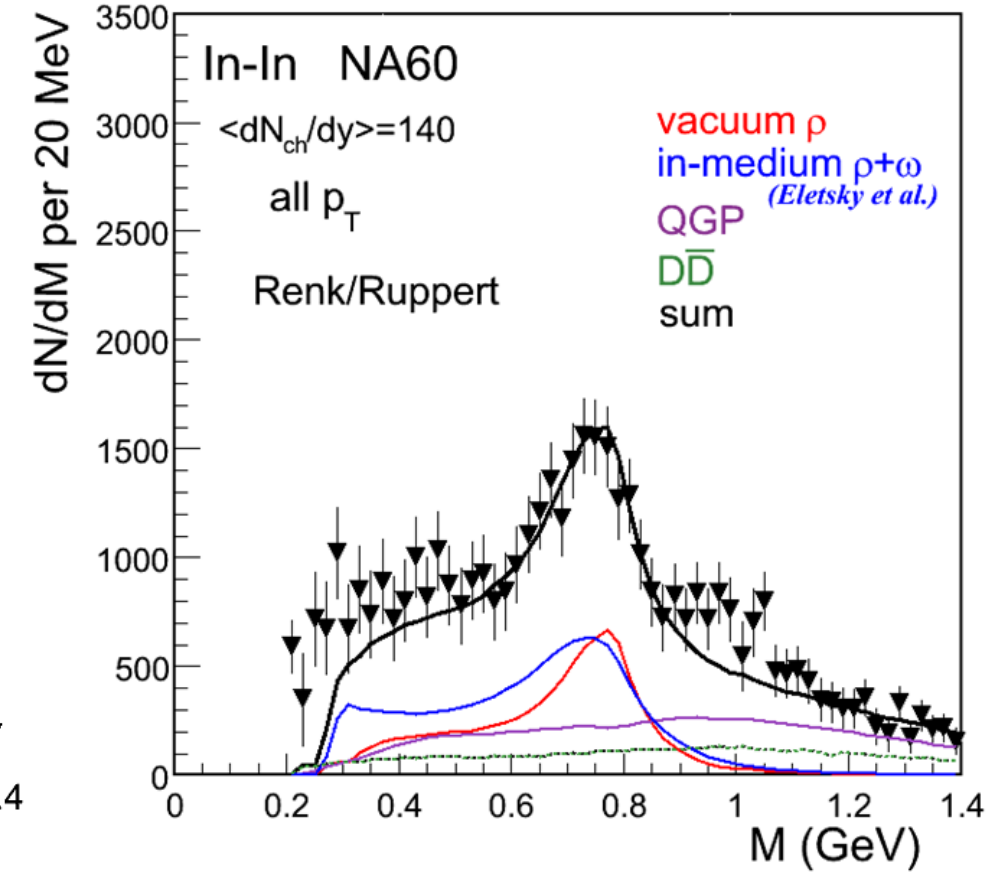
- data not acounted for in mass range $M_{\mu\mu}$ > 1 GeV

di-muon pairs with invariant mass > 1 GeV

H. van Hees and R. Rapp, PRL 99 (2006) 102301



J. Ruppert et al., hep-ph/0706.1934



- yield above 1 GeV attributed to hadronic processs like 4π annihilation (possibly augmented by chiral mixing)

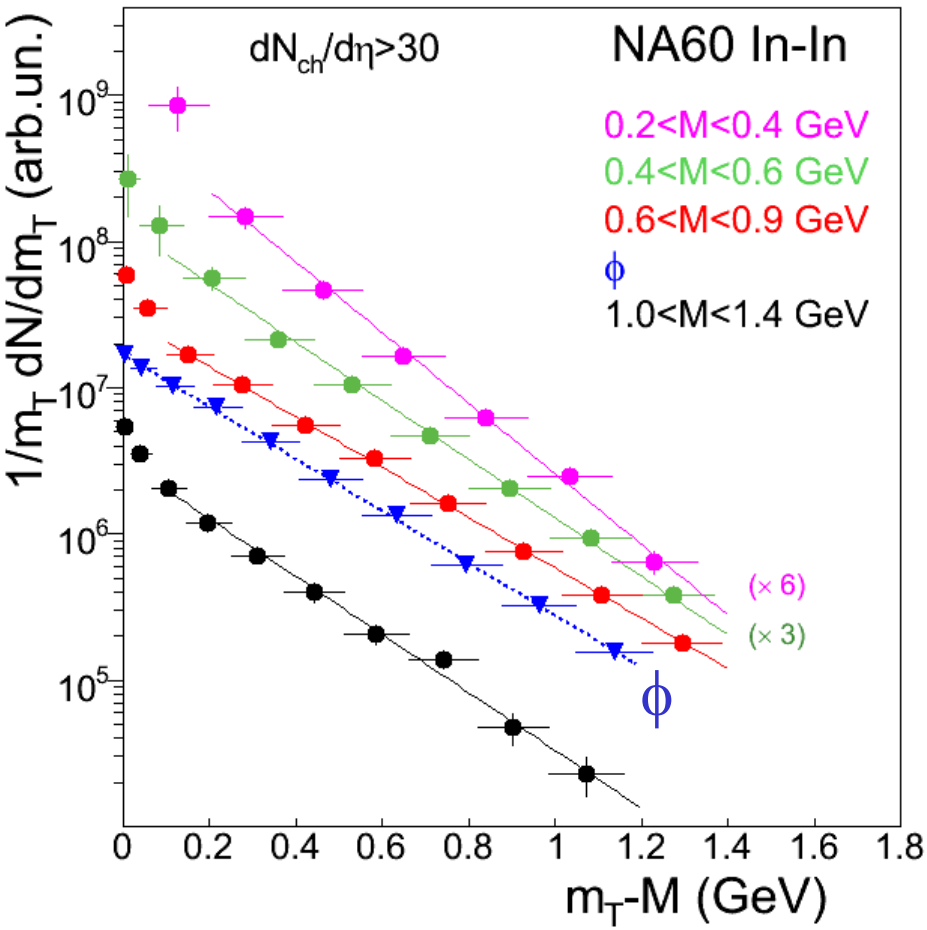
- yield above 1 GeV dominated by partonic processes like $q\bar{q}\rightarrow\mu^+\mu^-$

$\Rightarrow$ to be distinguished experimentally by information from p_t spectra ?

NA60@CERN/SPS

R. Arnaldi et al., PRL 100 (2008) 022302

m_t-dependence of the excess



$$m_t = \sqrt{p_t^2 + M^2}$$

- all m_t spectra fit for p_t >0.4 GeV with:

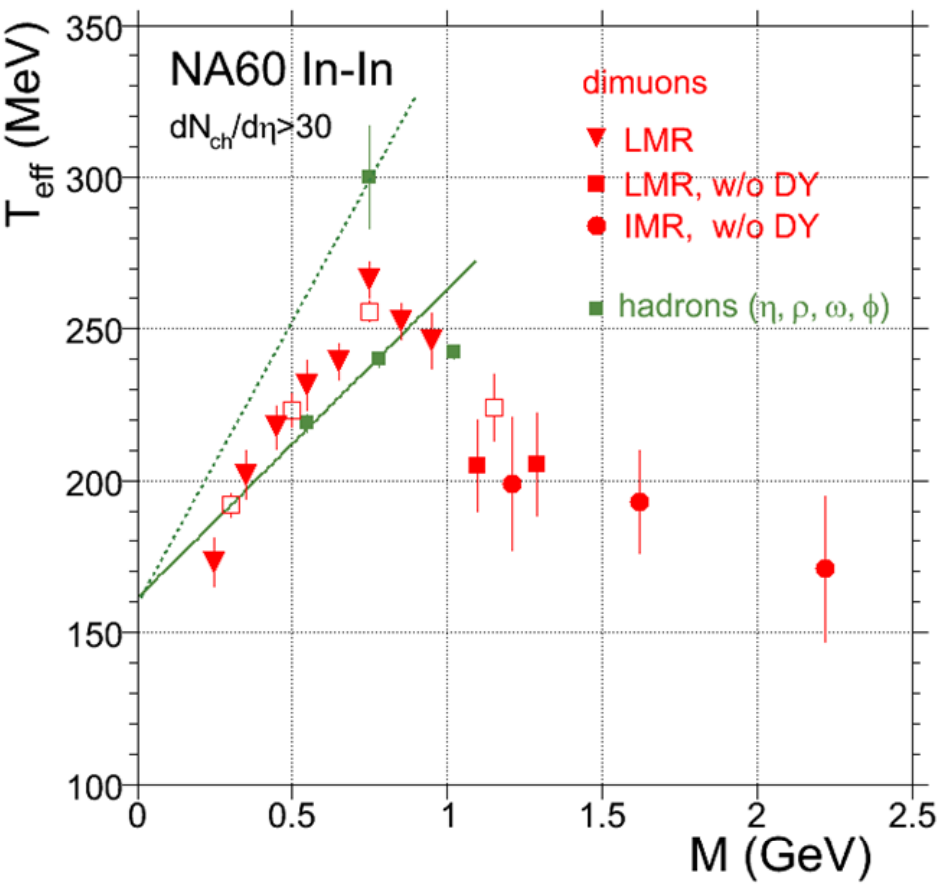
$$\frac{1}{m_t} \cdot \frac{dN}{dm_t} \sim e^{-\frac{m_t}{T_{eff}}}$$

- steepening at low m_t; not observed for hadrons like Φ
- monotonic flattening of spectra with increasing di-muon mass up to $M_{\mu\mu}$ =1 GeV
- steeper slope for $M_{\mu\mu}$ > 1 GeV
- hadron spectra determined at freeze out
- di-muon spectra are superposition from all fireball stages inculding:
  early emission: high T, low flow
  late emission: low T; high flow

$\Rightarrow$ nature of emitting source

NA60@CERN/SPS

R. Arnaldi et al., PRL 100 (2008) 022302



- hadrons show expected flow pattern: $T_{eff} \sim M$
  however, hierarchy of freeze out: different hadrons have different couplings to pions; maximal for ρ; minimal for Φ

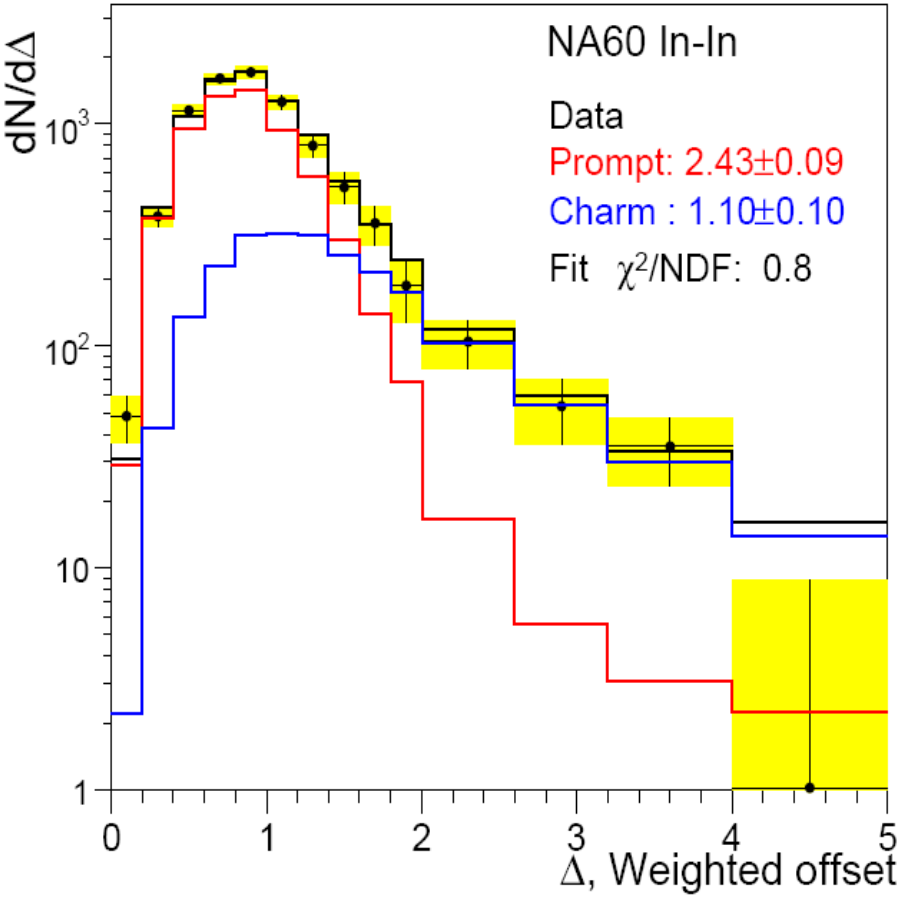
- nearly linear rise of T_{eff} with di-muon mass for $M_{\mu\mu} < 1$GeV consistent with radial flow of a hadronic source: $\pi\pi \rightarrow \rho \rightarrow \mu\mu$

- drop of T_{eff} at $M_{\mu\mu} \approx 1$ GeV interpreted as transition to low-flow source of e.g. partonic origin

- first observation of radial flow of thermal di-leptons; mass dependence of T_{eff} tool to identify nature of the emitting source; mostly partonic radiation for $M_{\mu\mu} > 1$ GeV ?

NA60: di-muons in the intermediate mass range

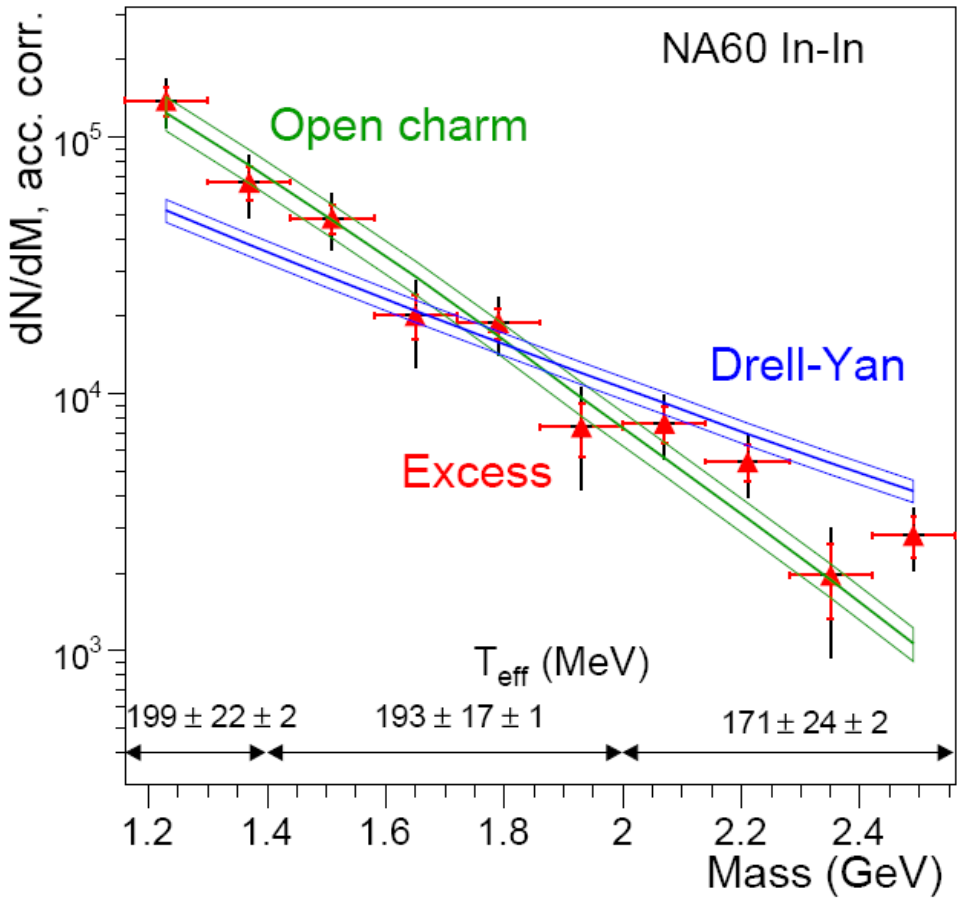
- Separation of prompt muon production from semi-leptonic open charm decays (discrimination prompt from off-vertex muons)



fit of weighted offset distribution with charm decay and prompt contributions

⇒ excess due to prompt muons

- decomposition of total di-muon yield into Drell-Yan, open charm and prompt excess



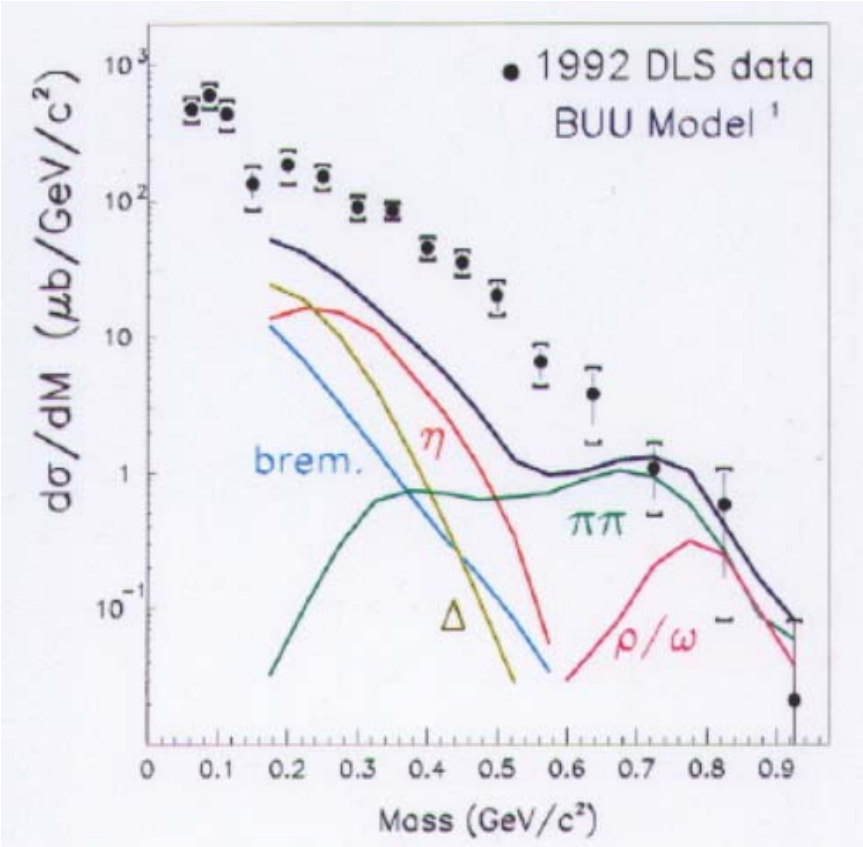
excess and open charm have similar slopes; excess = thermal radiation (ambiguity (NA50) resolved)

Di-electron production in A+A collisions at 1-2 AGeV

DLS@LBL

R. Porter et al., PRL 79 (1997) 1229

Ca+Ca → e^+e^- +X at 1 AGeV



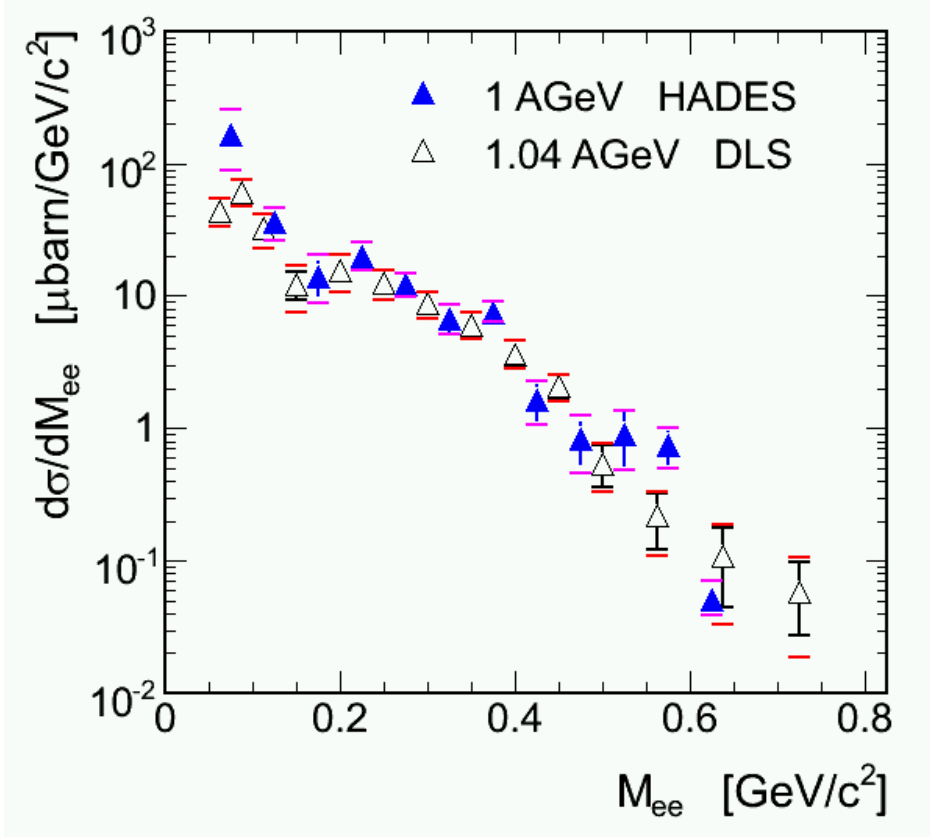
„DLS-puzzle“:

e^+e^- yield enhanced compared to post-freeze-out hadronic cocktail

HADES@GSI

G. Agakishiev et al., PLB 663 (2008) 43

C+C→ e^+e^- +X

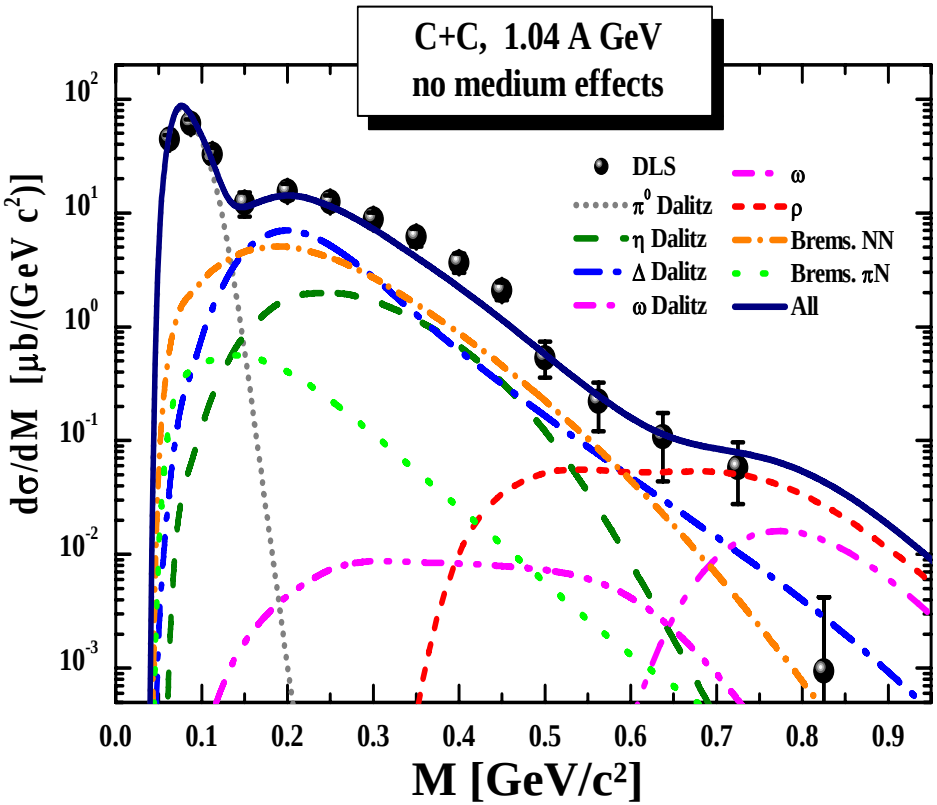


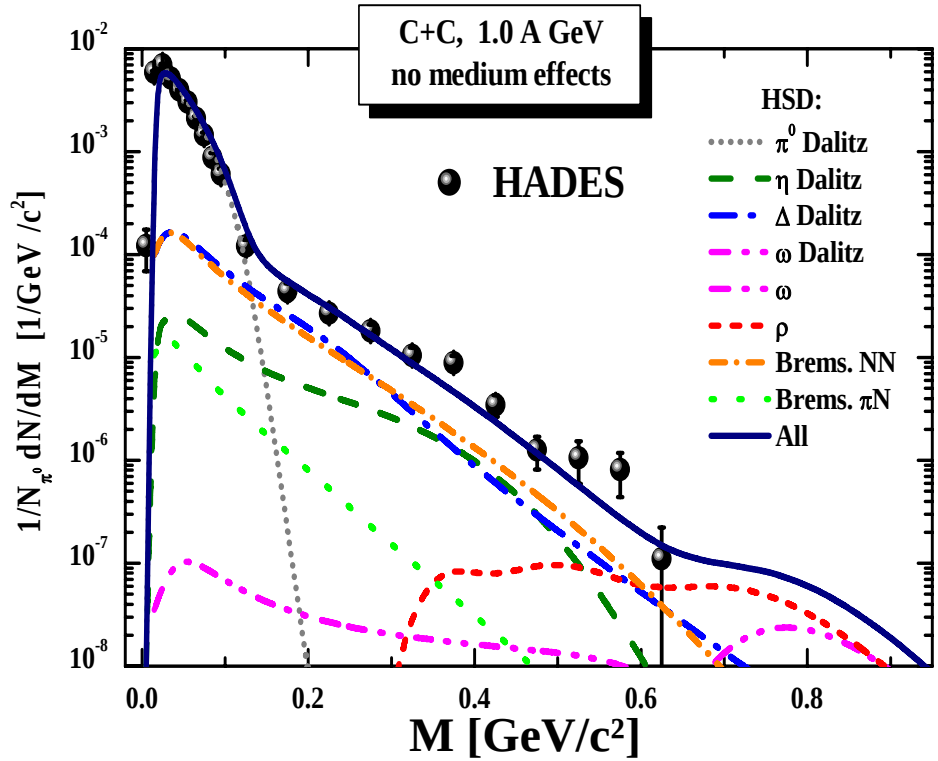
dilepton enhancement confirmed !!

comparison to transport model calculations

comparison of DLS and HADES-data to HSD-calculations

E. Bratkovskaya and W.Cassing, nucl-th/0712.0635





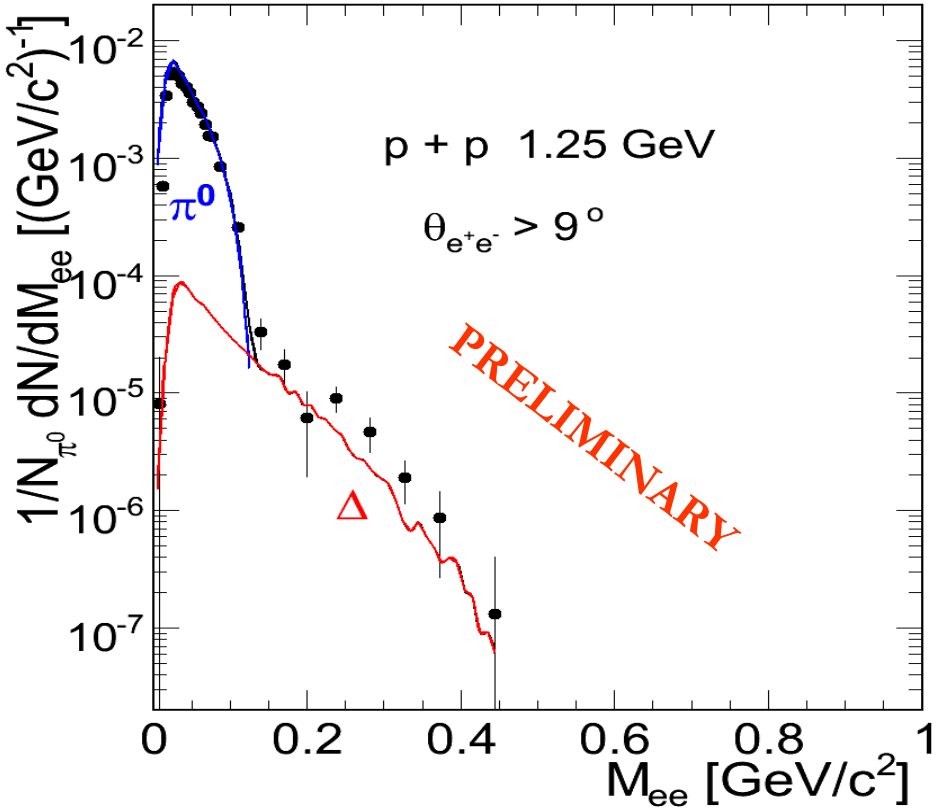
- new treatment of bremsstrahlung: R. Shyam and U. Mosel, PRC 67 (2003) 065202; L.P. Kaptari, B. Kämpfer, NPA 764 (2006) 338
- pn - bremsstrahlung and $\Delta \rightarrow e^+e^-$ N Dalitz decay dominant ?

$\Rightarrow$ experimental test by comparing to p+p and p+n reactions

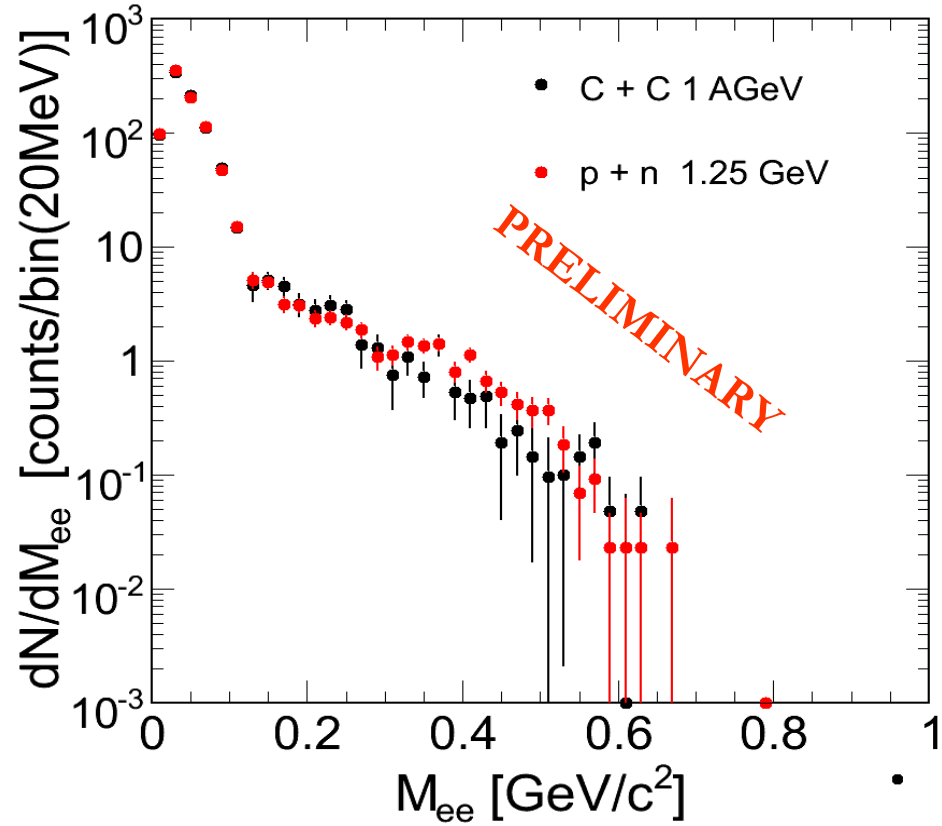
HADES@GSI

comparison of C+C data to p+p and p+n collisions (from d+p at 1.25 GeV)

normalized to p+p elastic scattering



normalized to the same π^0 yield

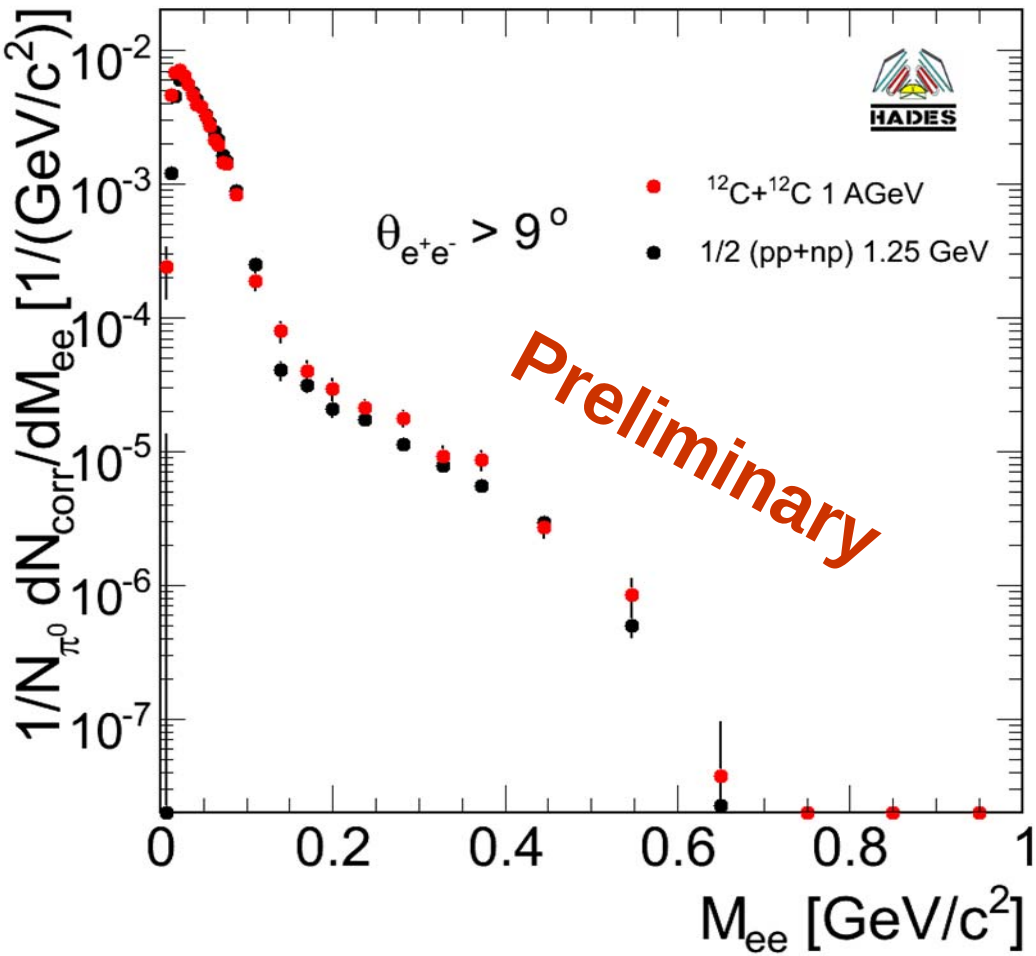


- $\Delta \rightarrow e^+e^-$ N seems to explain e^+e^- yield in p+p at 1.25 GeV

- $e^+ e^-$ invariant mass spectrum in C+C and p+n very similiar
  $\Rightarrow$ p+n collisions (bremsstrahlung ?) dominant in C+C at 1.25 GeV

HADES@GSI

comparison of C+C data to N-N collisions (from d+p at 1.25 GeV)



- dilepton spectra from C+C and N+N are almost identical after normalizing to the π^0 yield

⇒ at ≈1 AGeV dilepton yield in light A+A collisions (m_{ee} < 0.6 GeV) reproduced by properly scaling measured e^+e^- production in N+N reactions

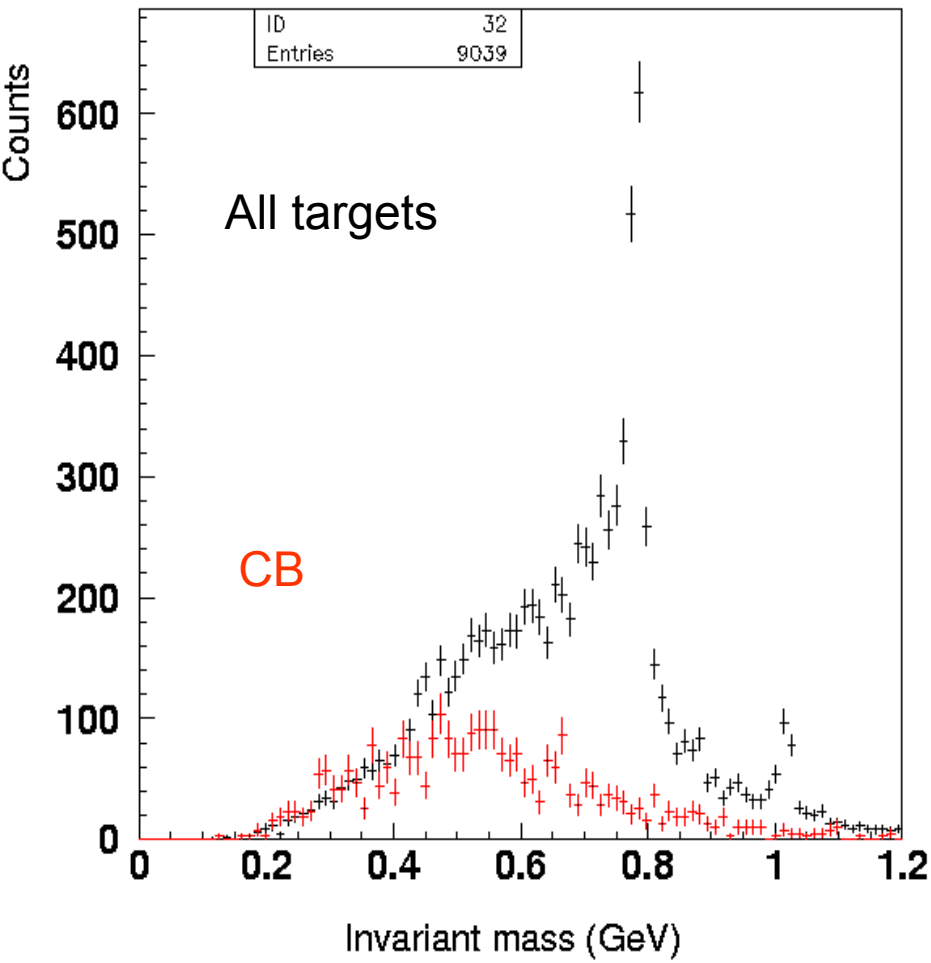
⇒ there is no dilepton enhancement in the 1 AGeV energy range

- e^+e^- yield in A+A underestimated theoretically because of insufficient description of N+N → e^+e^- +X; (p-n bremsstrahlung ??)

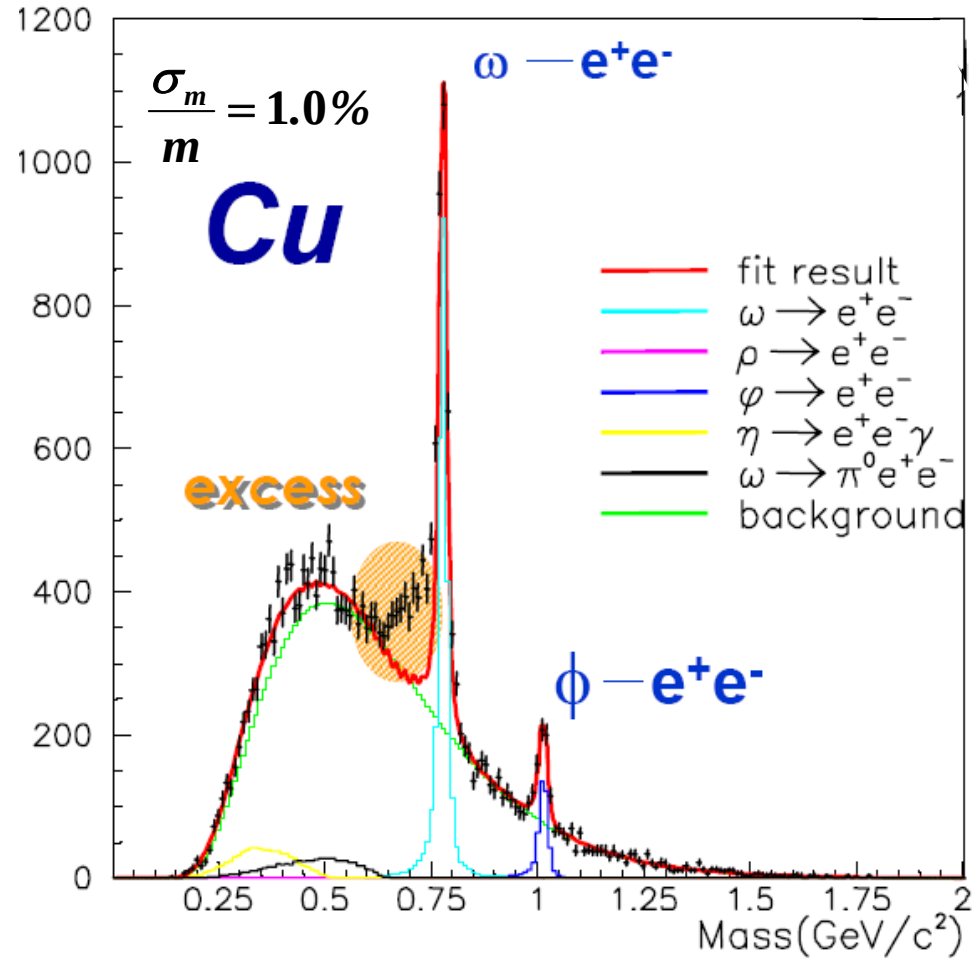
e^+e^- invariant mass spectra from γ- and p- induced reactions

JLAB-CLAS: G7 $\gamma A \rightarrow e^+e^- + X$

E_γ = 0.6-3.8 GeV



KEK-E325: p (12 GeV) A→ ρ, ω +X



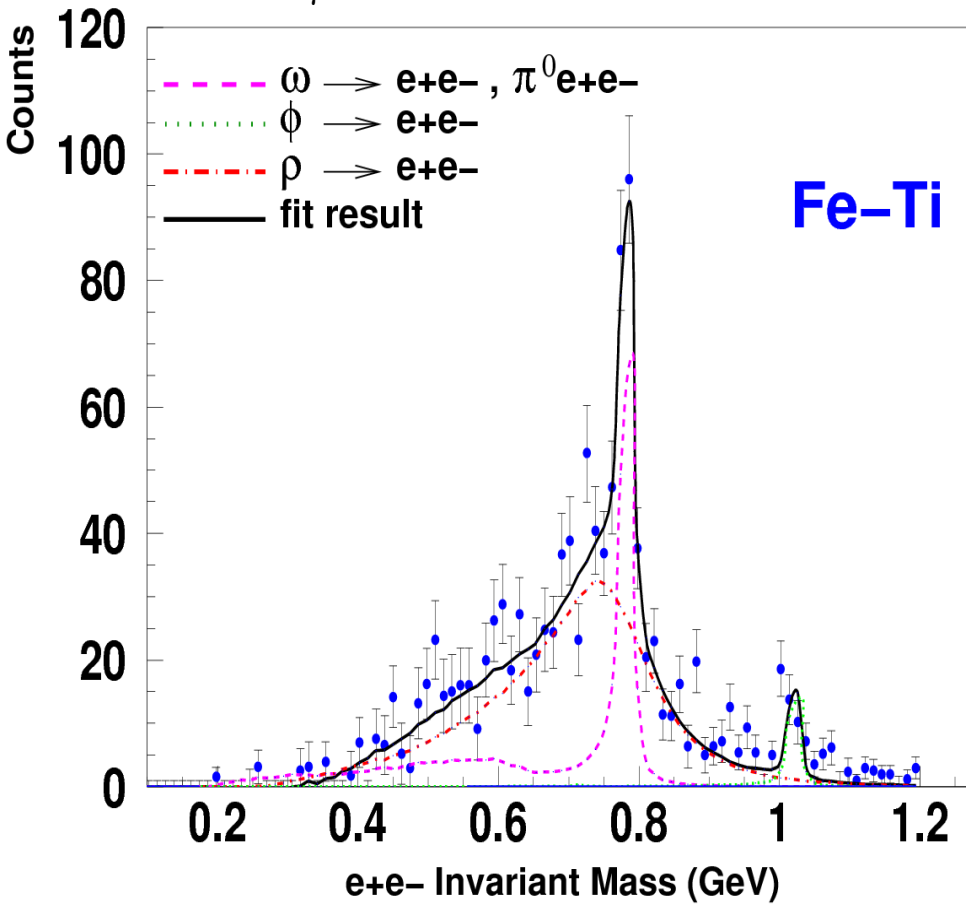
ω, ϕ -peaks observed;

additional yield above combinatorial background assigned to $\rho \rightarrow e^+e^-$

e^+e^- invariant mass spectra from γ- and p- induced reactions

JLAB-CLAS: G7 $\gamma A \rightarrow e^+e^- + X$

E_γ = 0.6-3.8 GeV

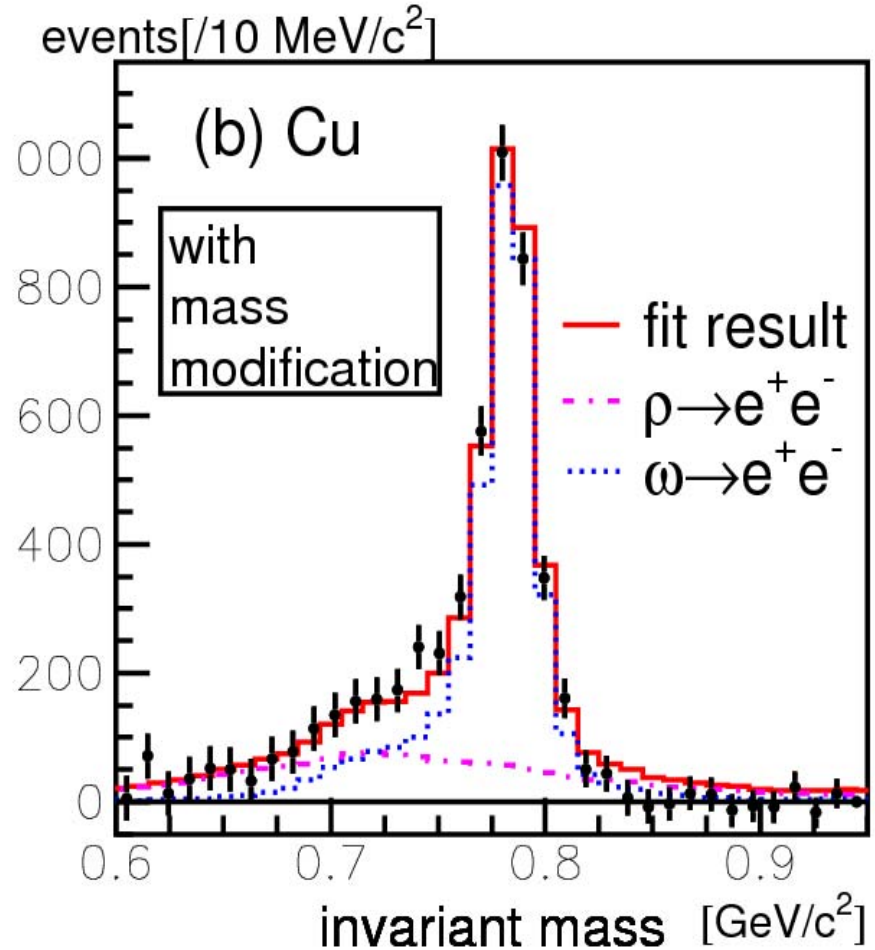


ρ slightly broadened; no mass shift

R. Nasseripour et al., PRL 99 (2007) 262302

No consistent picture!!

KEK-E325: p (12 GeV) $A \rightarrow \rho, \omega + X$



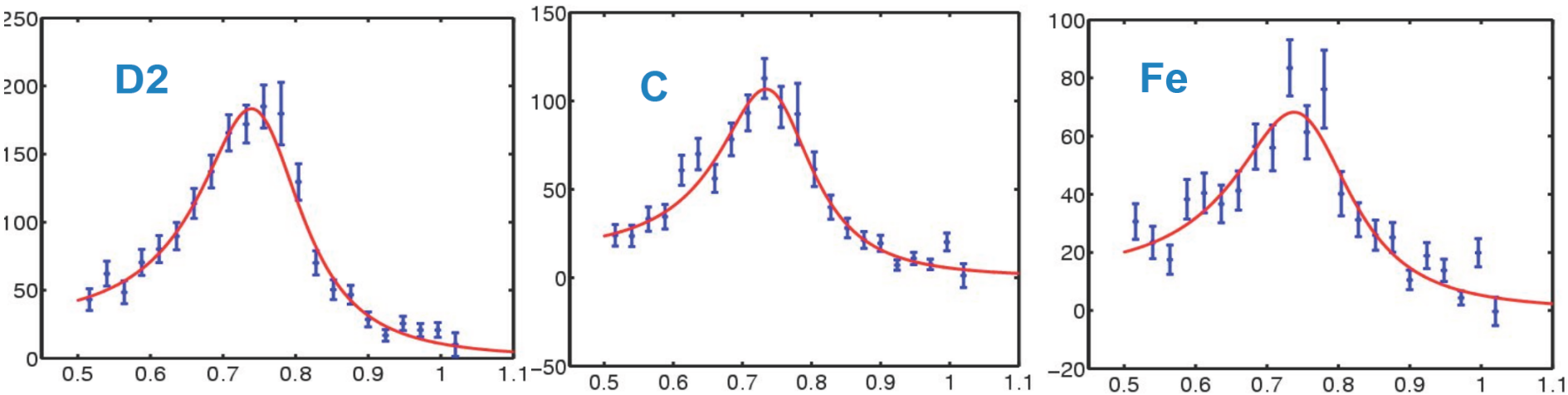
ρ shifted in mass: $m_\rho = m_0\left(1 - 0.092\frac{\rho}{\rho_0}\right)$;

no broadening!! Surprising !!

M. Naruki et al., PRL 96 (2006) 092301

In-medium ρ spectral function from Jlab-experiment

R. Nasseripour et al., PRL (2007) 262302



Invariant mass m_{ee} [GeV]

target	mass [MeV]	width [MeV]
D_2	770.3±3.2	185.2±8.6
C	762.5±3.7	176.4±9.5
Fe-Ti	779.0±5.7	217.7±14.5

compared to vacuum (PDG):
m = 775.5 ±0.4; Γ=149.4 ±1.0

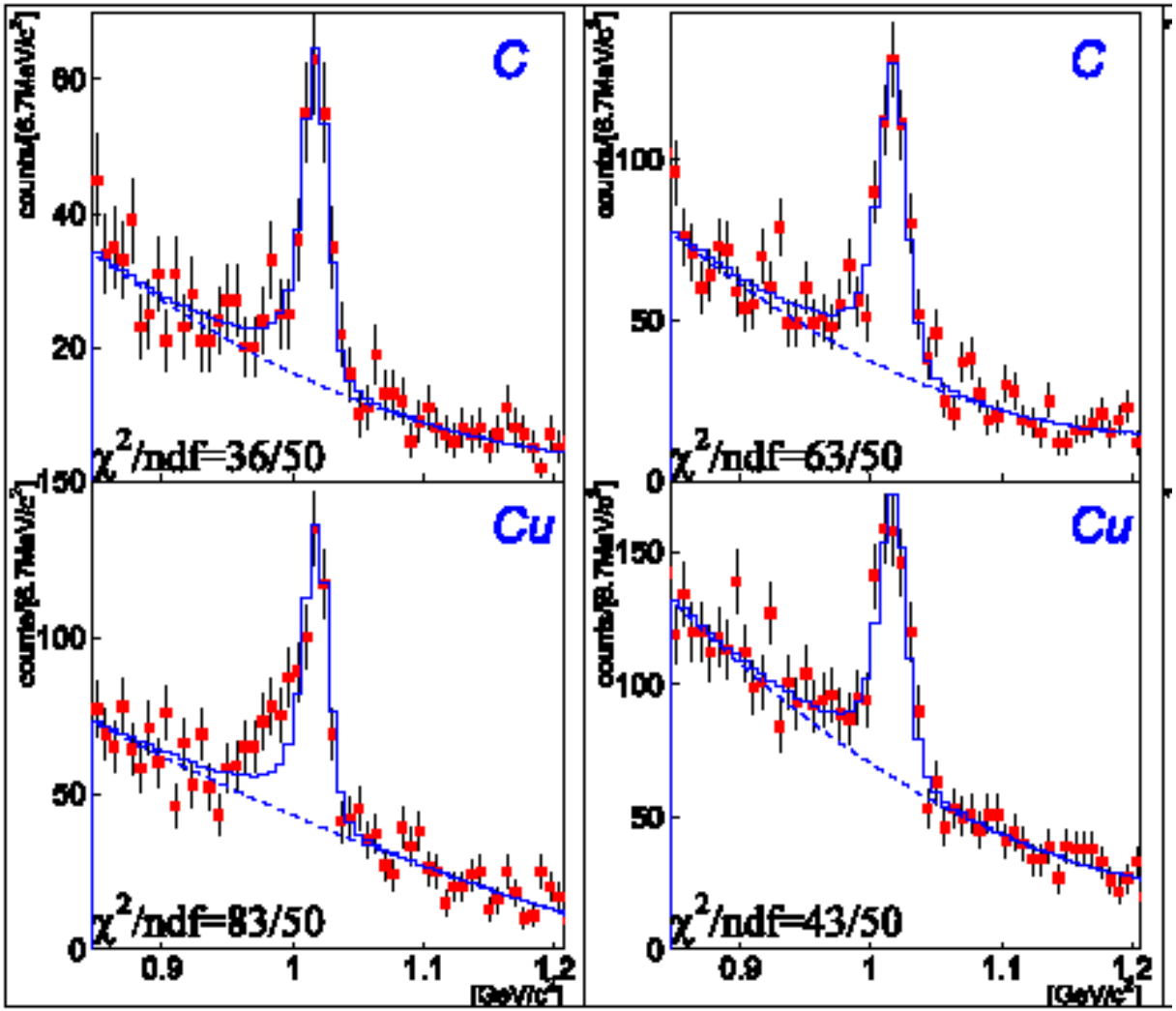
⇒ no mass shift but broadening by up to 45%; no modifications beyond standard nuclear many body effects

Note: detector acceptance only for ρ meson momenta > 0.8 GeV/c; not sensitive to medium modifications expected for p_ρ < 500 MeV/c

Φ - meson in the nuclear medium

KEK-E325: p (12 GeV) A→ ρ, ω +X; Φ → e^+e^-

$\beta\gamma<1.25$ (Slow)	$1.25<\beta\gamma<1.75$



R.Muto et al.,
PRL 98 (2007) 042501

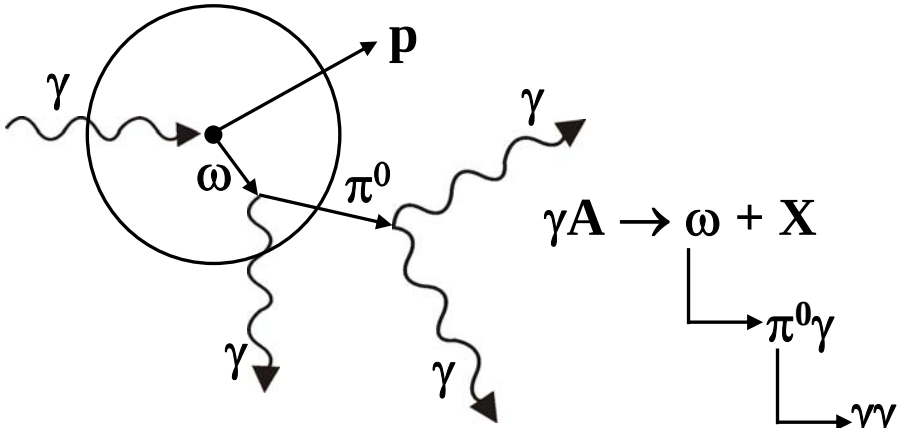
- mass shift of Φ- meson for low recoil momenta in Cu:

$$m_\Phi = m_0\left(1-0.04\frac{\rho}{\rho_0}\right)$$

- increase in width by factor 3.6

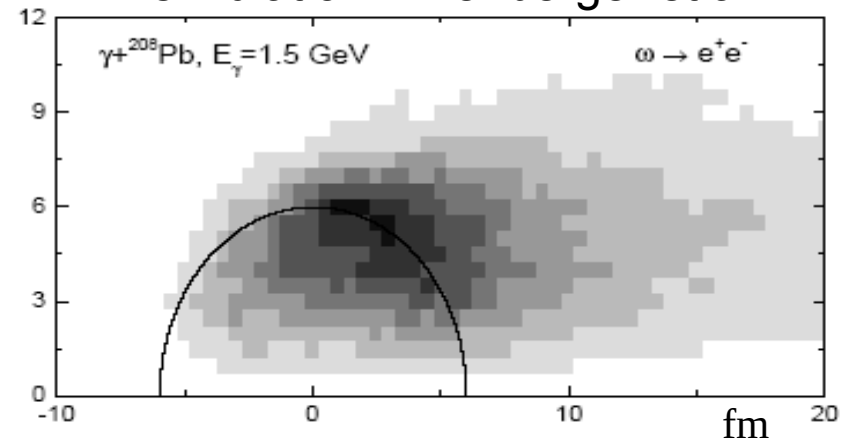
ω-mass in nuclei from photonuclear reactions

J.G.Messchendorp et al.,
Eur. Phys. J. A 11 (2001) 95

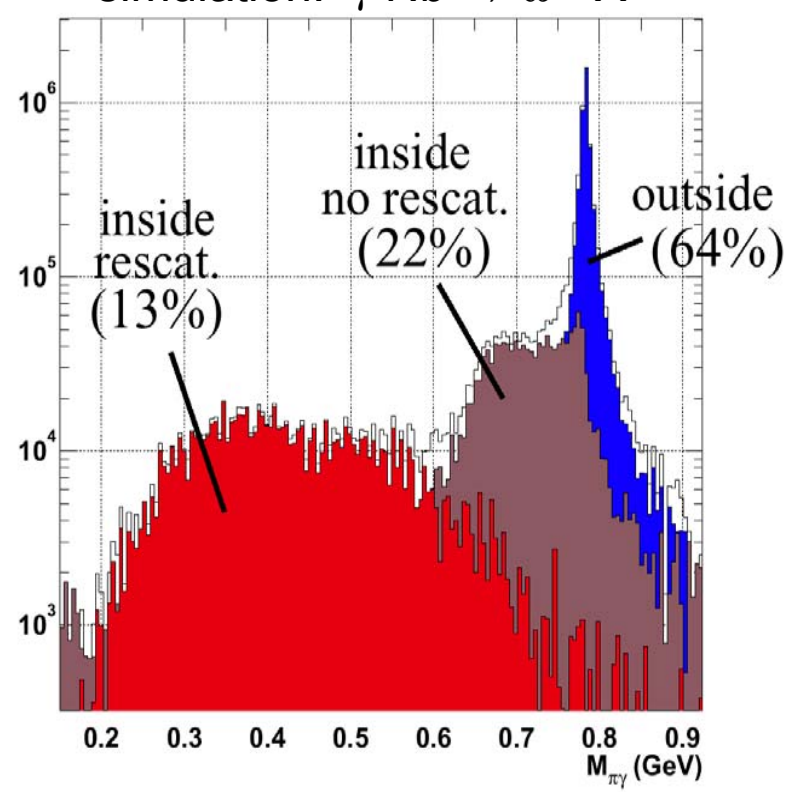


$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$

simulation: Effenberger et al.



simulation: γ Nb → ω +X



advantage:

- $\pi^0\gamma$ large branching ratio (8 %)
- no ρ-contribution ($\rho \to \pi^0\gamma$: $7 \cdot 10^{-4}$)

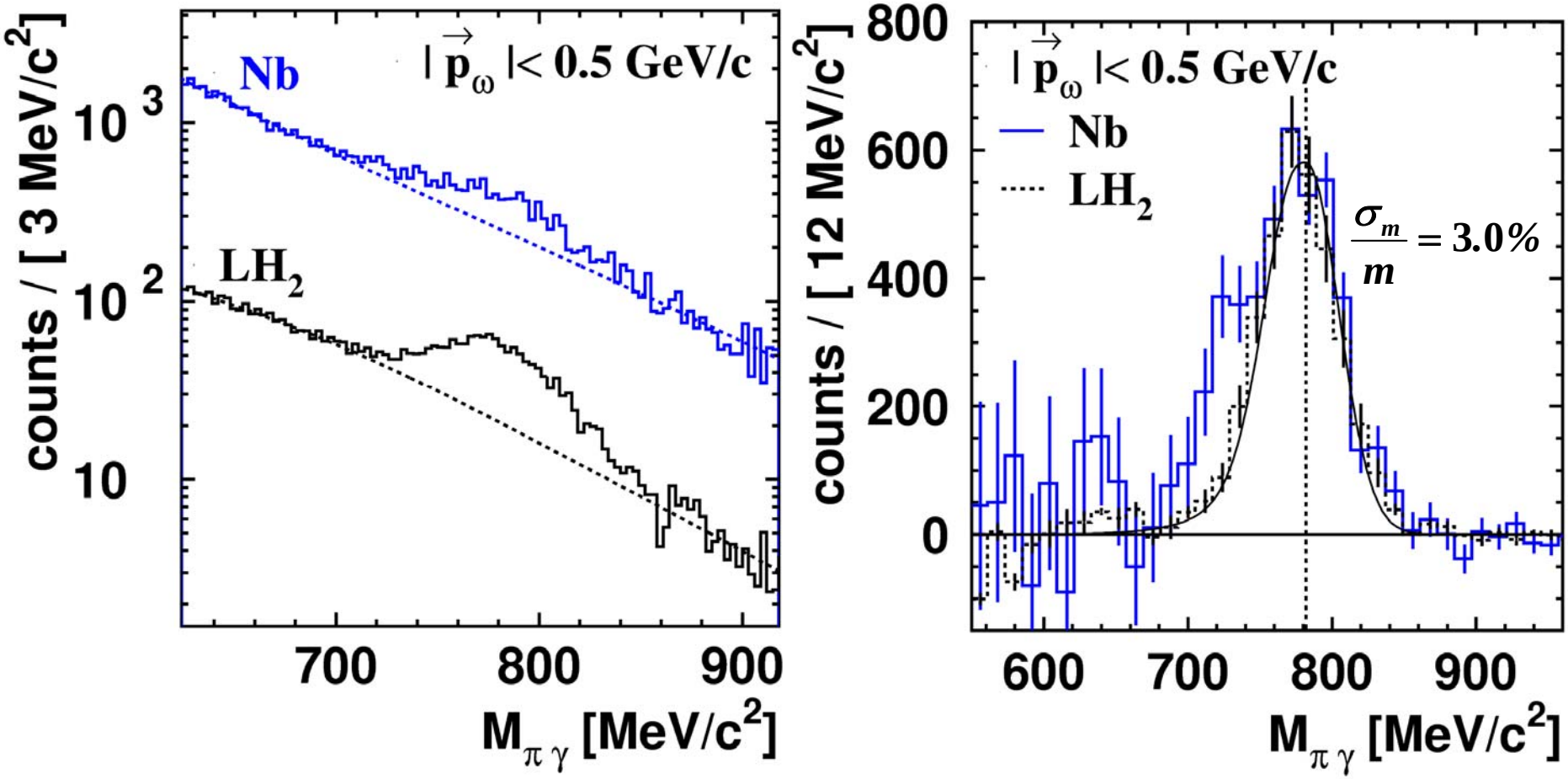
disadvantage:

- π^0-rescattering

CBELSA/TAPS: inclusive $\omega \to \pi^0\gamma$ signal for LH_2 and Nb target

D. Trnka et al., PRL 94 (2005) 192203

after background subtraction



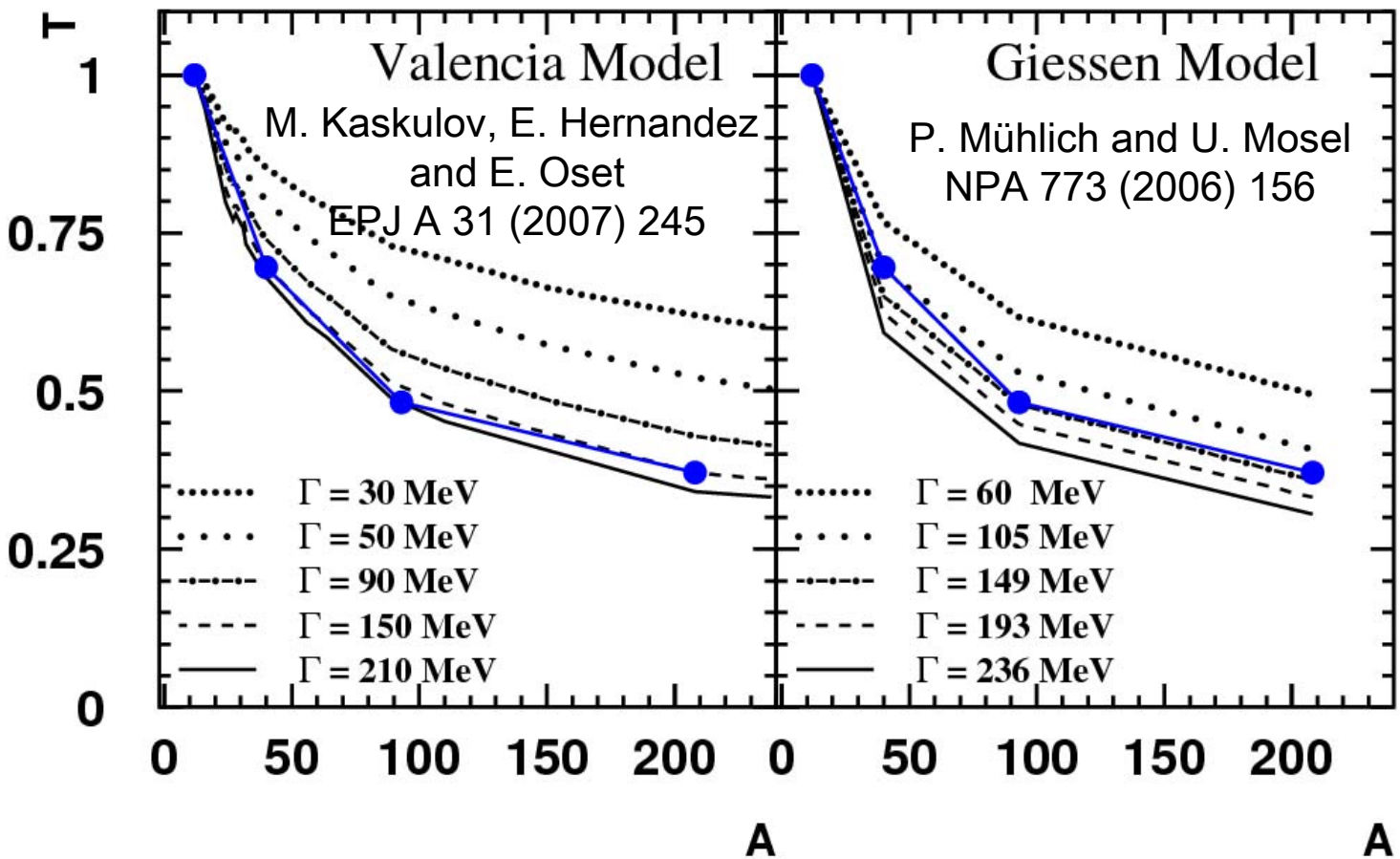
- difference in line shape of ω signal for proton and nuclear target !!
  consistent with drop of in-medium omega mass by 14% at $\rho = \rho_0$
- however, signal sensitive to background subtraction !!
  experiment repeated with ≈ 10 times the statistics; analysis ongoing

access to in-medium ω width

in-medium ω width proportional to ω absorption: $\Gamma(\vec{\rho},|p_\omega|) \propto \rho v \sigma_{abs}$

transparency ratio: $T_A = \dfrac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}}$ normalization to carbon!!

M. Kotulla et al, PRL 100 (2008) 192302



comparison to data $\Gamma(\rho_0,\langle|\vec{p}_\omega|\rangle \approx 1.1$ GeV/c) ≈ 130-150 MeV

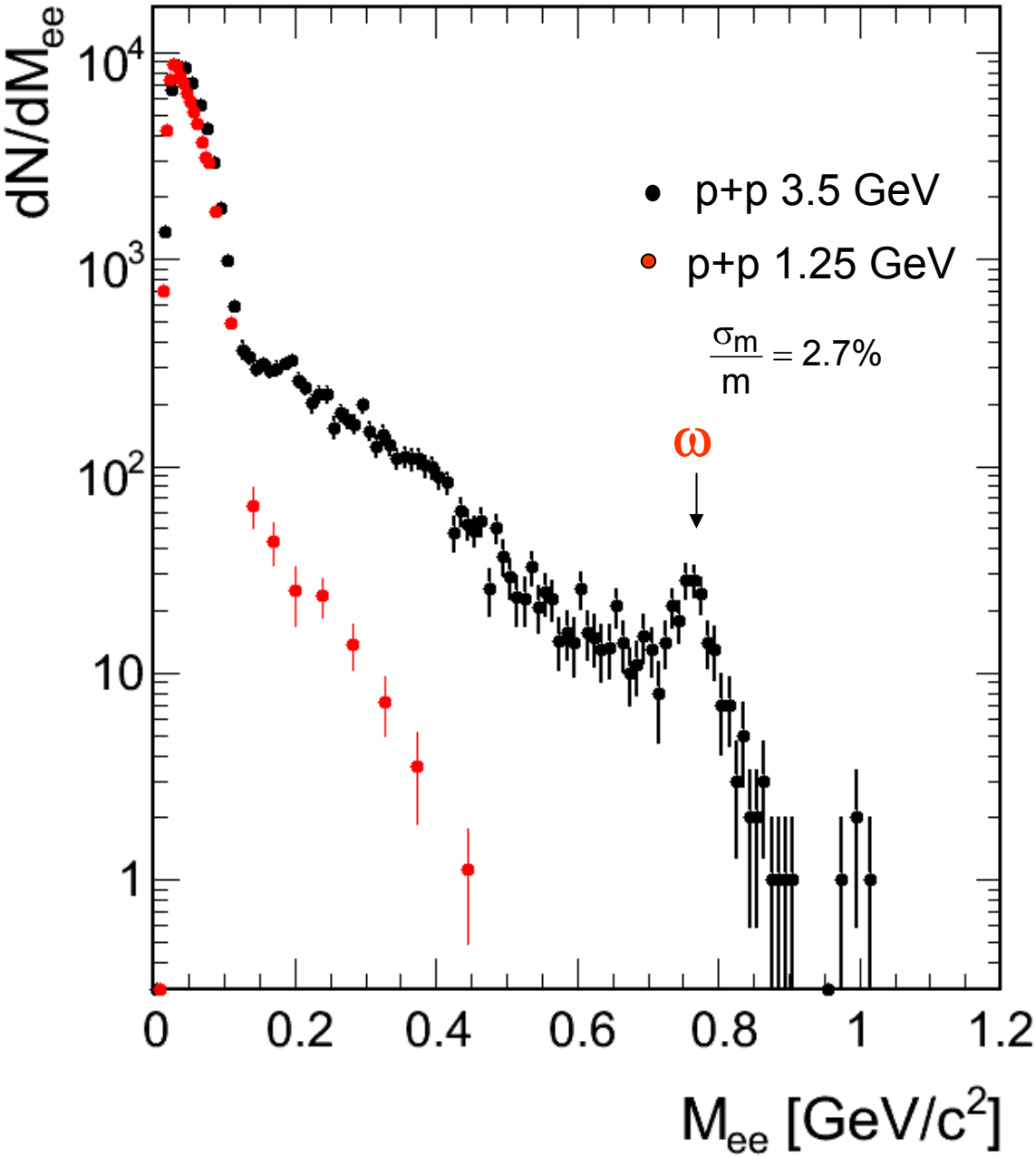
ω is broadened in the medium by a factor ≈16!!

Current status of in-medium studies

	M.Naruki et al., PRL 96 (2006) R. Muto et al., PRL 98 (2007)	R.Nasseripour et al., PRL 99 (2007)	D. Trnka et al, PRL 94 (2005) M. Kotulla et al. PRL 100 (2008)	D. Adamova et al., nucl-ex/0611022	R. Arnaldi et al., PRL 96 (2006)
	KEK	**Jlab**	**CBELSA/TAPS**	**CERES**	**NA60**
reaction	pA 12 GeV	γA 0.6-3.8 GeV	γA 0.7-2.5 Gev	Au+Au 158 AGeV	In+In 158 AGeV
momentum acceptance	p > 0.5 GeV/c	p > 0.8 GeV/c	p > 0.0 GeV/c	p_t > 0.0 GeV/c	p_t > 0.0 GeV/c
ρ	$\frac{\Delta m}{m} = -9\%$	Δm ≈ 0 some broadening		broadening favoured over density dependent mass shift	Δm ≈ 0 strong broadening
ω	no broadening		$\frac{\Delta m}{m} \approx -14\%$ $\frac{\Gamma_\omega(\rho_0)}{\Gamma_\omega} \approx 16$		
Φ	$\frac{\Delta m}{m} = -3.4\%$ $\frac{\Gamma_\Phi(\rho_0)}{\Gamma_\Phi} = 3.6$				

despite of enormous progress in the experiments no fully consistent picture reached as yet ⇒ further precision experiments needed !!

$\omega \rightarrow e^+e^-$ signal (HADES)



reference measurement on free proton done

ready for pA production run planned for Sept/Oct 2008

summary

hard photons: only upper bounds for direct photons from thermalized source in ultra-relativistic A+A collisions in non-RHIC experiments

dileptons: excess of e^+e^-, $\mu^+\mu^-$ pairs over post-freeze-out hadronic decays established by HELIOS, CERES and NA60;
attributed to annihilation of thermal pions in fireball:

$$\pi\pi \rightarrow \rho \rightarrow e^+e^- (\mu^+\mu^-);$$

$\Rightarrow$ space-time averaged in-medium ρ spectral function:
ρ broadening, no mass shift
NA60: for $M_{\mu\mu} > 1$ GeV evidence for low-flow (partonic?) source

$\Rightarrow$ dilepton yield in C+C in 1 AGeV energy regime (DLS, HADES) reproduced by scaling dilepton production in N+N reactions:
no enhancement; dilepton yield underestimated theoretically because of insufficient description of elementary reactions:
$N+N \rightarrow e^+ e^- + X$ (p-n bremsstrahlung ?)

$\Rightarrow$ elementary reactions $\gamma,p \rightarrow A \Rightarrow e^+e^- + X$ yield partially conflicting results on medium modifications of ρ-,ω-,ϕ- mesons; further experiments planned